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NUTRIENT MANAGEMENT IN THE POTOMAC ESTUARY

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Chesapeake Technical Support Laboratory
Middle Atlantic Region
Water Quality Office
Environmental Protection Agency

NUTRIENT MANAGEMENT

IN THE

POTOMAC ESTUARY

Technical Report 45

January 1971

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I

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INTRODUCTION

Historically, since the first sanitary survey was made in 1913 [30], the water quality of the upper Potomac Estuary has been degraded as a result of the discharge of either untreated or partially treated municipal wastewater from the Washington Metropolitan Area. Early surveys indicated that high coliform densities and low dissolved oxygen content were the two major water quality problems of the upper estuary. In the past decade, large nuisance populations of blue-green algae have also added to the water quality management problems of the upper and middle reaches of the estuary.

Initially, as part of the Chesapeake Bay-Susquehanna River Basins Comprehensive Planning Project* and now as an integral part of the Potomac Enforcement Conference, field water quality studies were undertaken, beginning in 1965, to define wastewater treatment requirements. The studies and concepts used to formulate a nutrient management program for the Potomac Estuary are presented in this paper.

Brief Description of the Study Area

The Potomac River Basin, with a drainage area of 14,670 square miles, is the second largest watershed in the Middle Atlantic States. From its headwaters on the eastern slope of the Appalachian Mountains,

* The Chesapeake Bay-Susquehanna River Basin Comprehensive Project was initiated by the Division of Water Supply and Pollution Control of the Public Health Service, U. S. Department of Health, Education, and Welfare.

the Potomac flows first northeasterly then generally southeasterly in direction some 400 miles to the Chesapeake Bay.

Upstream from Washington, D. C., the Potomac traverses the Piedmont Plateau to the Coastal Plain at the Fall Line. Below the Fall Line, the Potomac is tidal extending 114 miles southeastward and discharges into the Chesapeake Bay.

The tidal portion is several hundred feet in width at its uppermost reach near Washington and broadens to nearly six miles at its mouth. A shipping channel with a minimum depth of 24 feet is maintained upstream to Washington. Except for this channel and a few short reaches where depths up to 100 feet can be found, the tidal portion is relatively shallow with an average depth of approximately 18 feet.

Of the 3.3 million people living in the entire basin, approximately 2.8 million reside in the upper portion of the Potomac Estuary within the Washington Metropolitan Area. The lower areas of the tidal portion, which drains 3,216 square miles, are sparsely populated.

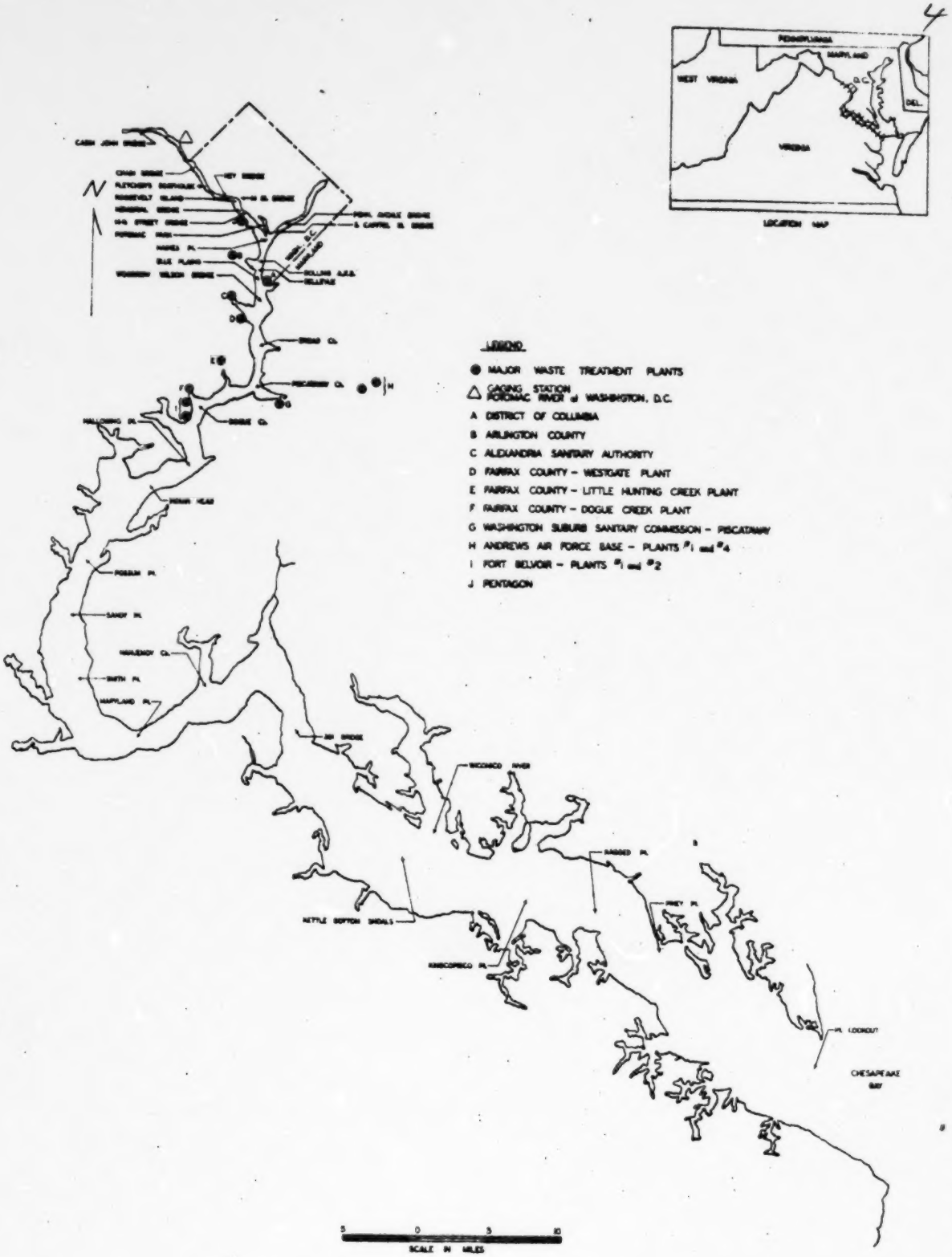
For purposes of discussion and investigation, the tidal portion of the Potomac River (Figure 1) has been divided into the three reaches described below:

Reach	Description	River Mile* (mi. below Chain Br.)	Volume (cu.ft.x10^8)
Upper	From Chain Bridge to Indian Head	0.0 to 30.0	93.50
Middle	From Indian Head to Rte. 301 Bridge	30.0 to 67.0	362.28
Lower	From Rte. 301 Bridge to Chesapeake Bay	67.0 to 114.4	1754.74

* All river miles are referenced to Chain Bridge which is located at the upper end of the tidal portion of the Potomac River.

The upper reach, although tidal, is essentially fresh water. The middle reach is normally the transition zone from fresh to brackish water. The lower reach is mesohaline with chloride concentrations near the Chesapeake Bay ranging from approximately 7,000 to 11,000 mg/l.

The average freshwater flow of the Potomac River near Washington before diversions for municipal water supply is 10,800 cubic feet per second (cfs) with a median flow of 6,500 cfs. The flow of the Potomac is characterized by flash floods and extremely low flows.



POTOMAC ESTUARY

Figure 1

CURRENT WATER QUALITY CONDITIONS

In the upper reach, approximately 325 million gallons per day (mgd) of wastewater is discharged mainly from municipal treatment facilities currently serving approximately 2.5 million people in the Washington Metropolitan Area. The largest wastewater treatment facility is the Blue Plains plant of the District of Columbia which serves approximately 1.8 million people. Wastewater discharged from the 18 facilities currently contributes 450,000, 24,000, and 60,000 lbs/day of ultimate oxygen demand* (UOD), phosphorus** and nitrogen respectively, to the waters of the upper estuary. The quantities of wastewater discharged into the middle and lower reaches is less than 5.0 mgd and thus very insignificant when compared to the upper reach.

Low dissolved oxygen (DO) concentrations, often less than 1.0 mg/l during summer, occur in the upper reach as a result of the oxidation of 200,000 and 240,000 lbs/day of carbonaceous and nitrogenous UOD respectively. Since the summer of 1969, the high fecal coliform densities (over 50,000 MPN/100 ml) previously observed near the wastewater discharges have been significantly reduced (less than 1,000 MPN/100 ml) by effective continuous chlorination.

* Ultimate oxygen demand is basically the sum of 1.45 times the 5-day biochemical oxygen demand and 4.57 times the unoxidized nitrogen.

** Phosphorus concentrations or loadings in this paper are given as phosphorus (P) except when specifically designated as PO_4.

The concentrations or forms of phosphorus and nitrogen in the Potomac Estuary are a function of wastewater loadings, temperature, freshwater inflow, distance from the Chain Bridge, and biological activity. As shown in Figure 2, the inorganic phosphorus varied considerably for the six stations presented from March 1969 through September 1970. The concentration at Hains Point, which is located at the upper end of the tidal excursion of the major wastewater discharges, was fairly uniform averaging 0.1 mg/l as P (0.3 mg/l as PO_4). At Woodrow Wilson Bridge, which is located below the Blue Plains wastewater discharge, the inorganic phosphorus increased appreciably with concentrations over 0.8 mg/l (2.5 mg/l as PO_4) occuring during low-flow periods as those in the months of May-July 1969, October-November 1969, and September 1970. The remaining four downstream stations had progressively lower concentrations.

The total phosphorus concentration closely parallels that of inorganic phosphorus. In the upper reach, the ratio of total phosphorus to inorganic phosphorus ranges from 1.1 to 1.5. The ratio is higher in the middle reach normally varying from 1.5 to 2.0 with the lower reach having a range from approximately 2.0 to 2.5.

The concentration of nitrite and nitrate nitrogen at Hains Point and Woodrow Wilson Bridge varies almost inversely with that of phosphorus (Figure 3). The NO_2 + NO_3 concentrations as a result of land runoff were the highest during periods of high river flows as in July

INORGANIC PHOSPHATE CONCENTRATION as PO_4
POTOMAC ESTUARY
1969 - 1970

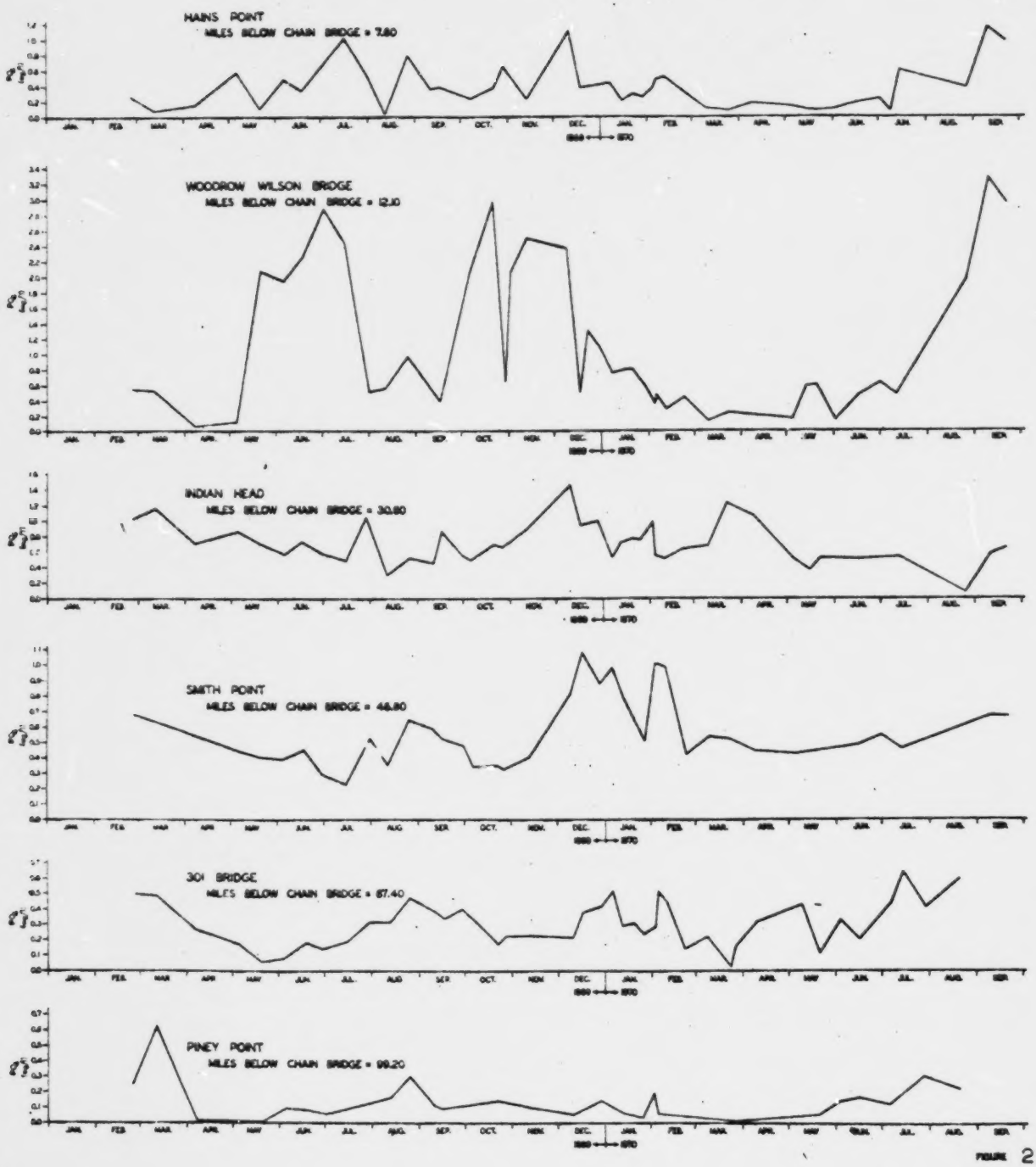

HAINS POINT
MILES BELOW CHAIN BRIDGE = 7.80
WOODROW WILSON BRIDGE
MILES BELOW CHAIN BRIDGE = 12.10
INDIAN HEAD
MILES BELOW CHAIN BRIDGE = 30.80
SMITH POINT
MILES BELOW CHAIN BRIDGE = 46.80
301 BRIDGE
MILES BELOW CHAIN BRIDGE = 67.40
PINEY POINT
MILES BELOW CHAIN BRIDGE = 99.20
JAN. FEB. MAR. APR. MAY JUN. JUL. AUG. SEP. OCT. NOV. DEC. JAN. FEB. MAR. APR. MAY JUN. JUL. AUG. SEP.
1969 ← → 1970

FIGURE 2

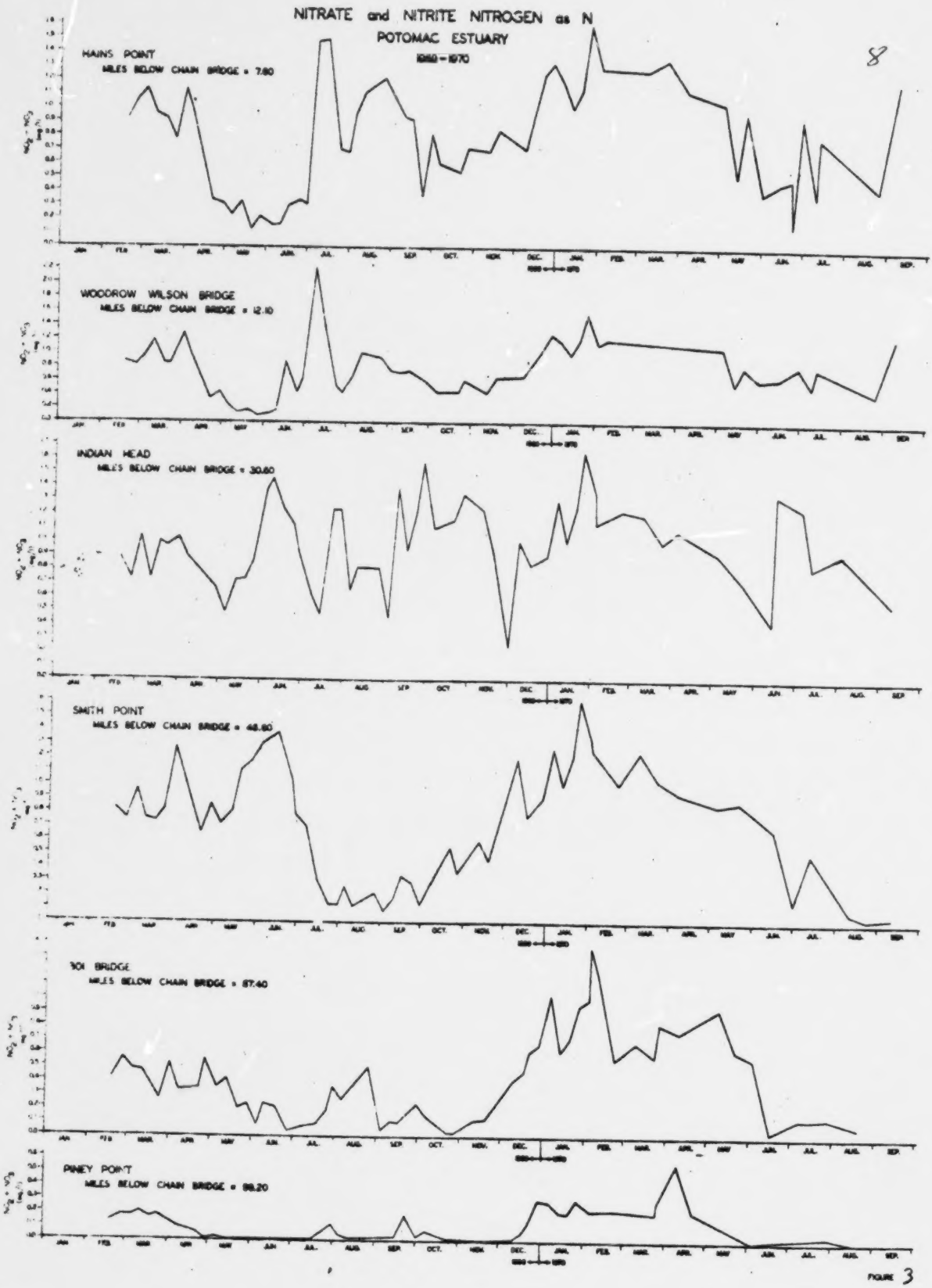

NITRATE and NITRITE NITROGEN as N
POTOMAC ESTUARY
1969 - 1970
8
HAINS POINT
MILES BELOW CHAIN BRIDGE = 7.80
WOODROW WILSON BRIDGE
MILES BELOW CHAIN BRIDGE = 12.10
INDIAN HEAD
MILES BELOW CHAIN BRIDGE = 30.60
SMITH POINT
MILES BELOW CHAIN BRIDGE = 46.80
301 BRIDGE
MILES BELOW CHAIN BRIDGE = 67.40
PINEY POINT
MILES BELOW CHAIN BRIDGE = 88.20

FIGURE 3

and August 1969, and during the late winter and early spring months of 1969 and 1970. During these flow conditions, the inorganic phosphorus concentration was lowest (Figure 2).

The increase of NO_2 + NO_3 at Indian Head as compared to Woodrow Wilson Bridge in May-June 1969, September-November 1969, and July 1970 is the result of the conversion of ammonia (from the wastewater treatment plant discharges) to nitrates. The low concentration of NO_2 + NO_3 in the summer months at Smith Point is caused by uptake of algal cells as described later in this report. During winter months, algal utilization is much less thus the concentrations of nitrates are high as in the months of January through April 1970. At Piney Point, concentrations of NO_2 + NO_3 are usually less than 0.1 mg/l on an annual basis.

As shown in Figure 4, the concentration of ammonia nitrogen is also affected by flow and temperature conditions. Although large quantities of ammonia are discharged from wastewater treatment facilities into the Potomac near Woodrow Wilson Bridge, ammonia concentrations at Indian Head during the summer months are low due to nitrification.

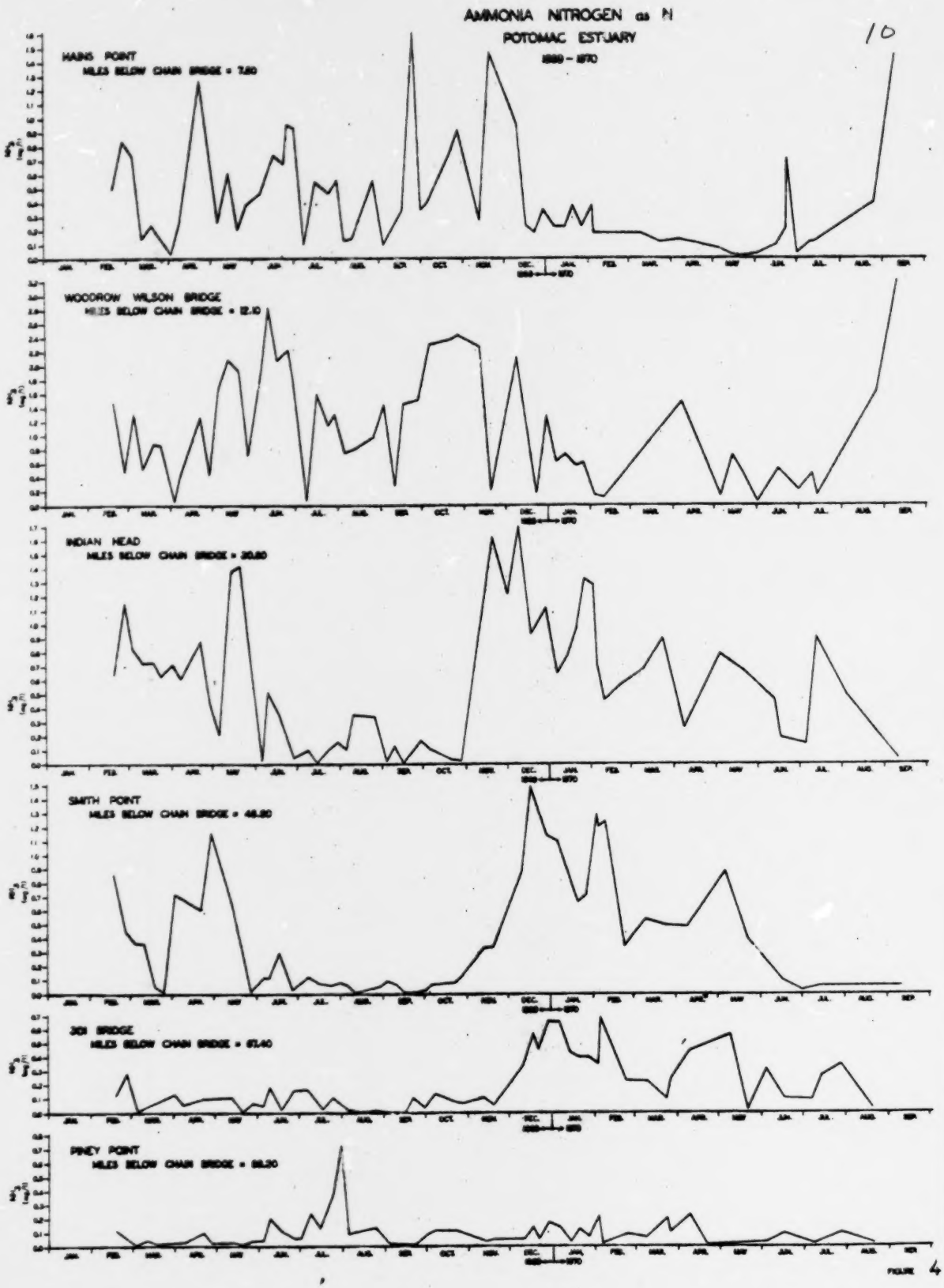

AMMONIA NITROGEN as N
POTOMAC ESTUARY
1969 - 1970
HAINS POINT
MILES BELOW CHAIN BRIDGE = 7.60
WOODROW WILSON BRIDGE
MILES BELOW CHAIN BRIDGE = 12.10
INDIAN HEAD
MILES BELOW CHAIN BRIDGE = 20.80
SMITH POINT
MILES BELOW CHAIN BRIDGE = 46.80
301 BRIDGE
MILES BELOW CHAIN BRIDGE = 67.40
PINEY POINT
MILES BELOW CHAIN BRIDGE = 88.30

FIGURE 4

During the summer and early fall months, the average ranges of pH, alkalinity, and free dissolved CO_2 (measured by titration) for the five stations in the upper and middle reaches were:

Location	pH (units)	Alkalinity (mg/l as $CaCO_3$)	Free Dissolved CO_2 (mg/l)
Chain Bridge	7.5 - 8.0	80 - 100	2 - 4
W. Wilson Bridge	7.0 - 7.5	90 - 110	8 - 12
Indian Head	7.2 - 8.0	70 - 90	6 - 10
Maryland Point	7.5 - 8.2	60 - 85	2 - 8
Rte. 301 Bridge	7.5 - 8.0	65 - 85	7 - 8

In the vicinity of the Woodrow Wilson Bridge, there is an increase in both alkalinity and CO_2 with a corresponding decrease in pH attributed to wastewater discharges. There is a decrease in both alkalinity and CO_2 with a corresponding increase in pH at the Indian Head and Maryland Point stations which are due to algal growths. In the lower estuary, the alkalinity and CO_2 increases while pH decreases. The algal standing crops are considerably smaller in this reach.

Salinity concentration as well as nutrient enrichment from wastewater discharges has a pronounced effect on the ecology of the estuary. Under summer and fall conditions, large populations of blue-green algae, primarily Anacystis sp. (Microcystis), are prevalent from the metropolitan area as far downstream as Maryland Point.

Under warm temperature and low-flow conditions, large standing crops of this alga develop forming "green mats" of cells. Chlorophyll a

concentrations (a measure of algal standing crop) range from approximately 50 to over 200 ug/l in these areas of dense growth which at times encompass approximately 50 miles of the upper and middle reaches of the estuary. These high chlorophyll levels are 5 to 10 times those reportedly observed in other eutrophic waters [5] [32]. During a dense bloom, the dry weight of cells ranges from 10 to 25 mg/l which is almost twice those reported for the Madison, Wisconsin lakes [22].

Chlorophyll a determinations for the upper reach and for the middle and lower reaches of the Potomac Estuary are presented in Figures 5 and 6, respectively. At Indian Head and Smith Point for 1965-1966 and 1969-1970, the chlorophyll a concentrations indicate that algal populations have not only increased in density in the latter years but have become more persistent over the annual cycle. At both stations, higher values of chlorophyll were measured during the 1969-1970 sampling cruises than during the 1965-1966 cruises even though flow conditions were more stable in 1965-1966. The occurrence of a spring bloom of diatoms was observed in 1969 and 1970 but not during the 1965-1966 cruises.

In the mesohaline portion of the lower reach of the Potomac Estuary, the algal populations are not as dense as in the freshwater portion. Nevertheless at times, large populations of marine phytoplankton (primarily the dinoflagellates Gymnodinium sp. and Amphidinium sp.) occur producing what are known as "red tides."

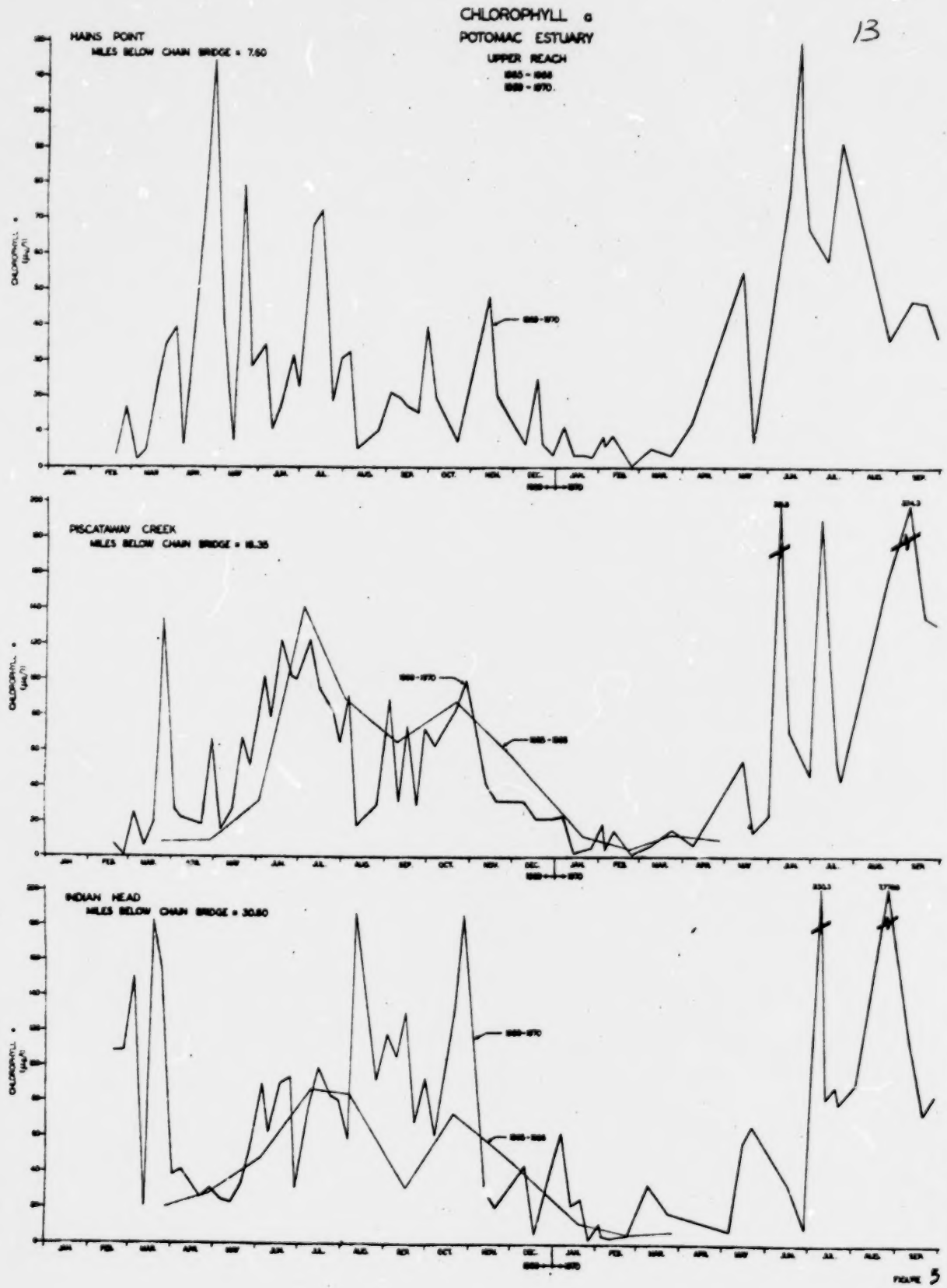

CHLOROPHYLL a
POTOMAC ESTUARY
UPPER REACH
1965 - 1968
1969 - 1970.
HAINS POINT
MILES BELOW CHAIN BRIDGE = 7.60
CHLOROPHYLL a (µg/l)
1969 - 1970
PISCATAWAY CREEK
MILES BELOW CHAIN BRIDGE = 18.35
CHLOROPHYLL a (µg/l)
1969 - 1970
1965 - 1968
INDIAN HEAD
MILES BELOW CHAIN BRIDGE = 30.80
CHLOROPHYLL a (µg/l)
1969 - 1970
1965 - 1968

FIGURE 5

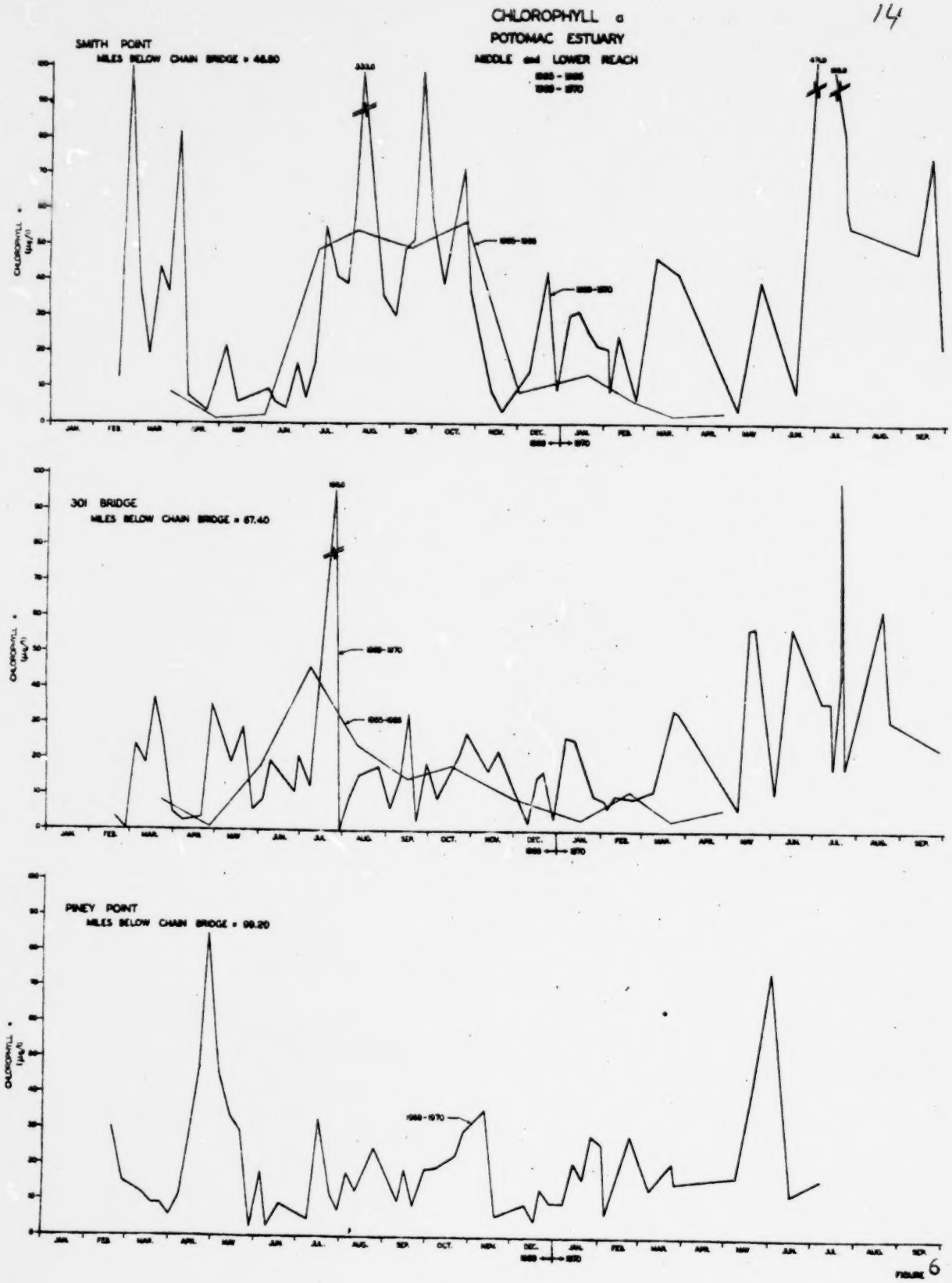

CHLOROPHYLL a
POTOMAC ESTUARY
MIDDLE and LOWER REACH
SMITH POINT
MILES BELOW CHAIN BRIDGE = 46.80
301 BRIDGE
MILES BELOW CHAIN BRIDGE = 67.40
PINEY POINT
MILES BELOW CHAIN BRIDGE = 98.20
CHLOROPHYLL a (µg/l)
JAN. FEB. MAR. APR. MAY JUN. JUL. AUG. SEP. OCT. NOV. DEC. JAN. FEB. MAR. APR. MAY JUN. JUL. AUG. SEP.

FIGURE 6

ECOLOGICAL TRENDS AS RELATED TO NUTRIENT ENRICHMENT

Since the first observations reported in 1913, the effect of the increased nutrients on the ecology of the upper Potomac Estuary has been dramatic (Figure 7). Historical invasions of nuisance plant growths in the upper Potomac Estuary can be inferred from several studies. Cumming [6] surveyed the estuary in 1913-1914 and noted the absence of plant life near the major waste outfalls with "normal" amounts of rooted aquatic plants on the flats or shoal areas below the urban area. No nuisance levels of rooted aquatic plants or phytoplankton blooms were noted.

In the 1920's, an infestation of water chestnut appeared in the waters of the Chesapeake Bay including the Potomac Estuary. This infestation was controlled by mechanical removal [23].

In September and October 1952, another survey of the reaches near the metropolitan area made by Bartsch [2] revealed that vegetation in the area was virtually nonexistent. While no massive phytoplankton blooms were reported, there was a noticeable increase in blue-green algae and diatoms when compared to the 1913-1914 studies.

In August and September 1959, a survey of the area was made by Stotts and Longwell [28]. Blooms of the nuisance blue-green alga Anacystis were reported in the Anacostia and Potomac Rivers near Washington.

In 1958 a rooted aquatic plant, water milfoil, developed in the waters of the Chesapeake Bay including the Potomac Estuary and created

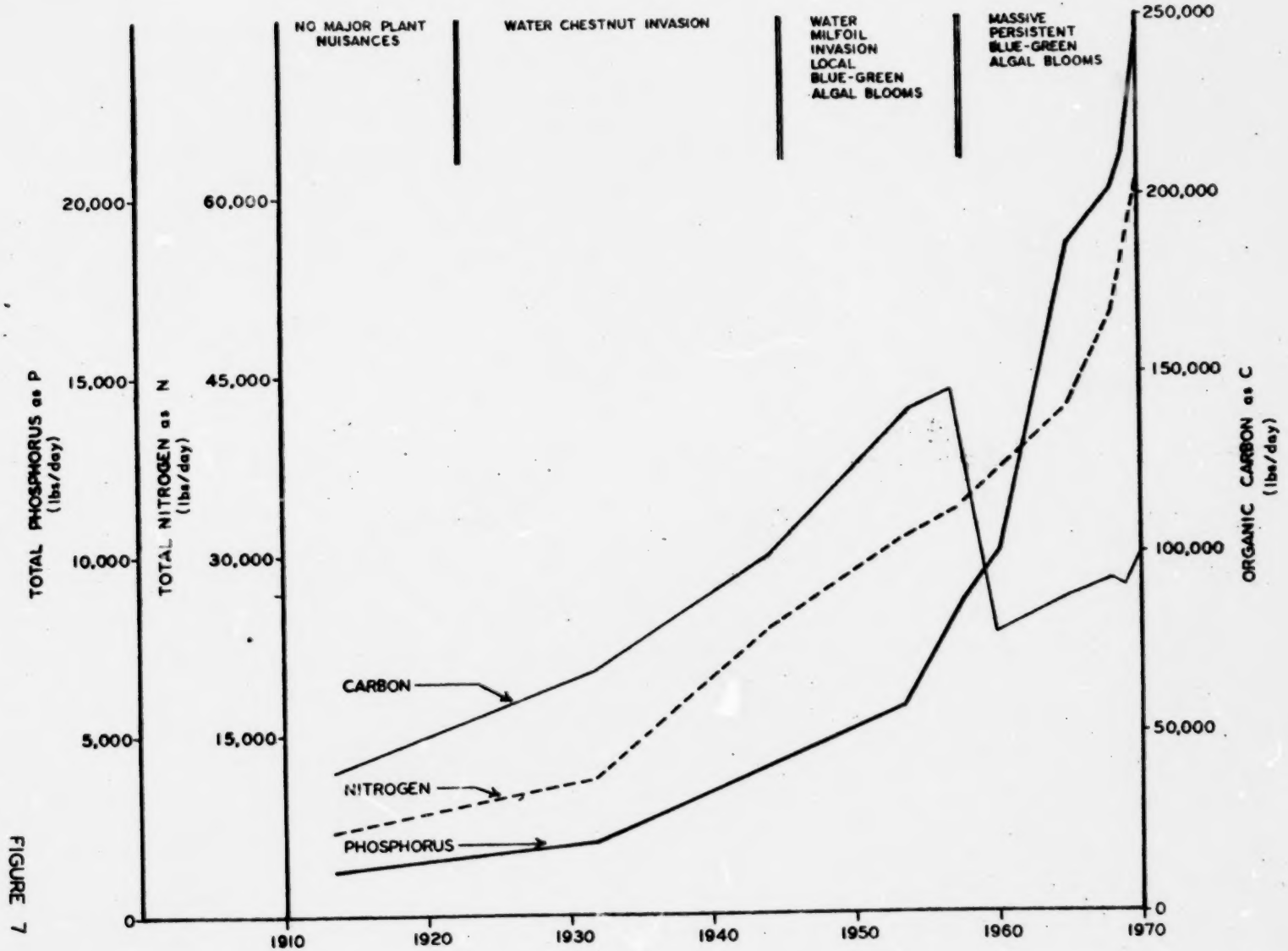

WASTEWATER NUTRIENT ENRICHMENT TRENDS AND ECOLOGICAL EFFECTS
UPPER POTOMAC TIDAL RIVER SYSTEM
NO MAJOR PLANT NUISANCES
WATER CHESTNUT INVASION
WATER MILFOIL INVASION LOCAL BLUE-GREEN ALGAL BLOOMS
MASSIVE PERSISTENT BLUE-GREEN ALGAL BLOOMS
TOTAL PHOSPHORUS as P (lbs/day)
TOTAL NITROGEN as N (lbs/day)
ORGANIC CARBON as C (lbs/day)
20,000
15,000
10,000
5,000
0
60,000
45,000
30,000
15,000
250,000
200,000
150,000
100,000
50,000
0
CARBON
NITROGEN
PHOSPHORUS
1910
1920
1930
1940
1950
1960
1970

FIGURE 7

nuisance conditions. The growth increased to major proportions by 1963, especially in the embayments from Indian Head downstream [8] and then dramatically disappeared beginning in late 1965. The decrease was presumably due to a natural virus [3].

Subsequent and continuing observations by the Chesapeake Technical Support Laboratory (CTSL) staff have confirmed persistent massive summer blooms of the blue-green alga Anacystis. Nuisance concentrations occur from the Washington Metropolitan Area downstream as far as Maryland Point [16].

From the above considerations, it would appear that nuisance conditions did not develop linearly with an increase in nutrients. Instead, the increase in nutrients appeared to favor the growth and thus the domination by a given species. As nutrients increased further, the species in turn was rapidly replaced by another dominant form. For example, water chestnut was replaced by water milfoil which in turn was replaced by Anacystis.

Figure 7 indicates that the massive blue-green algal blooms now occurring every summer since 1960 are associated with large phosphorus and nitrogen loading increases in the upper reaches of the Potomac River tidal system. The blooms have persisted since the early 1960's although the amount of organic carbon from wastewater has been reduced by almost 50 percent of that discharged prior to 1960. Moreover, the organic carbon loadings being discharged now are equal to those that were discharged in the early 1940's when there were no reported nuisance

conditions as a result of algal growth. These observations tend to suggest that the ecological changes have been caused by increases in nitrogen and phosphorus and not by organic carbon.

NUTRIENT SOURCES AND CONTROLLABILITY

A complete analysis of the nutrient sources in the upper Potomac Estuary has been made by Jaworski et al [17]. A summary of the three major sources is presented in Table 1 for low- and median-flow conditions. For low- and median-flows, the contribution from wastewater discharges of the three nutrients on a percentage basis is presented below:

Percentage from Wastewater Discharges

	Excluding Air-Water Interface			Including Air-Water Interface		
	Median Flow (%)		Low Flow (%)	Median Flow (%)		Low Flow (%)
Carbon	29	to	55	12	to	15
Nitrogen	60	to	90	59	to	89
Phosphorus	82	to	96	82	to	96

From the above tabulation, it can be concluded that the order of controllability of nutrients by wastewater treatment is (1) phosphorus, (2) nitrogen, and (3) carbon.

While 82 to 96 percent of the phosphorus entering the upper estuary can be controlled by removal at the wastewater treatment facilities, an additional reduction of phosphorus concentration occurs during periods of high runoff within the upper estuary itself. As reported by Aalto et al [1], large quantities of phosphorus (over 100,000 lbs/day) enter the upper estuary during high-flow periods at concentrations over 0.5 mg/l (1.5 mg/l as PO_4) during the rising portion of the river discharge hydrograph. However, high silt concentrations also accompany high flows.

Table 1

SUMMARY OF NUTRIENT SOURCES

Upper and Middle Reaches of the Potomac Estuary

Low-Flow Conditions

(Potomac River Discharge at Washington, D. C. = 1200 cfs)

	Land Runoff (lbs/day)	Wastewater Discharges (lbs/day)	Air-Water Interface (lbs/day)
Carbon	170,000	160,000*	950,000**
Nitrogen	6,700	60,000	1,600***
Phosphorus	1,000	24,000	0

Median-Flow Conditions

(Potomac River Discharge at Washington, D. C. = 6500 cfs)

Carbon	350,000	160,000*	950,000**
Nitrogen	40,000	60,000	1,600***
Phosphorus	5,300	24,000	0

* Of the 160,000 lbs/day, 60,000 lbs/day are discharged as inorganic carbon

** The potential CO_2 obtainable from the atmosphere was determined by using only 0.1 percent of the transfer rate of 0.6 $mg/cm^2/min$ as indicated by Riley and Skirrow [15]

*** Based on a nitrogen fixation rate of five lbs/acre/year as reported by Hutchinson [14]

Large amounts of phosphorus are sorbed upon the silt particles and removed from the water system as sedimentation occurs in the upper reach of the estuary.

This deposition was also observed in the summer of 1970 (Figure 8). During the month of June, the average flow of the Potomac at Washington was approximately 6,000 cfs with a daily contribution of approximately 2,000 lbs/day of phosphorus to the upper estuary. During the period from July 10 to July 11, 1970, the flow increased to over 47,000 cfs contributing over 70,000 lbs/day of phosphorus. By July 13, the flow decreased to less than 19,000 cfs with the flow on July 22 being less than 5,000 cfs and the phosphorus contribution decreased to less than 3,000 lbs/day.

Although there was some dilution of high phosphorus concentrations, the large sediment load reduced the overall phosphorus concentration by a minimum of 20 percent in the reaches upstream and downstream from the major wastewater sources at River Mile 12.0. (See profiles for July 13 and July 22, 1970) This reduction during periods of high flow would tend to add to the controllability of phosphorus as tabulated earlier. The high percentage from wastewater discharges, especially during the early months of the algal growing season and the large losses to the sediments during high-flow periods made phosphorus an ideal nutrient to manage.

In periods of extremely high runoff, the concentration of nitrate in the waters entering the Potomac Estuary from the upper basin also increases; and at times, over 300,000 lbs/day of nitrogen enters the

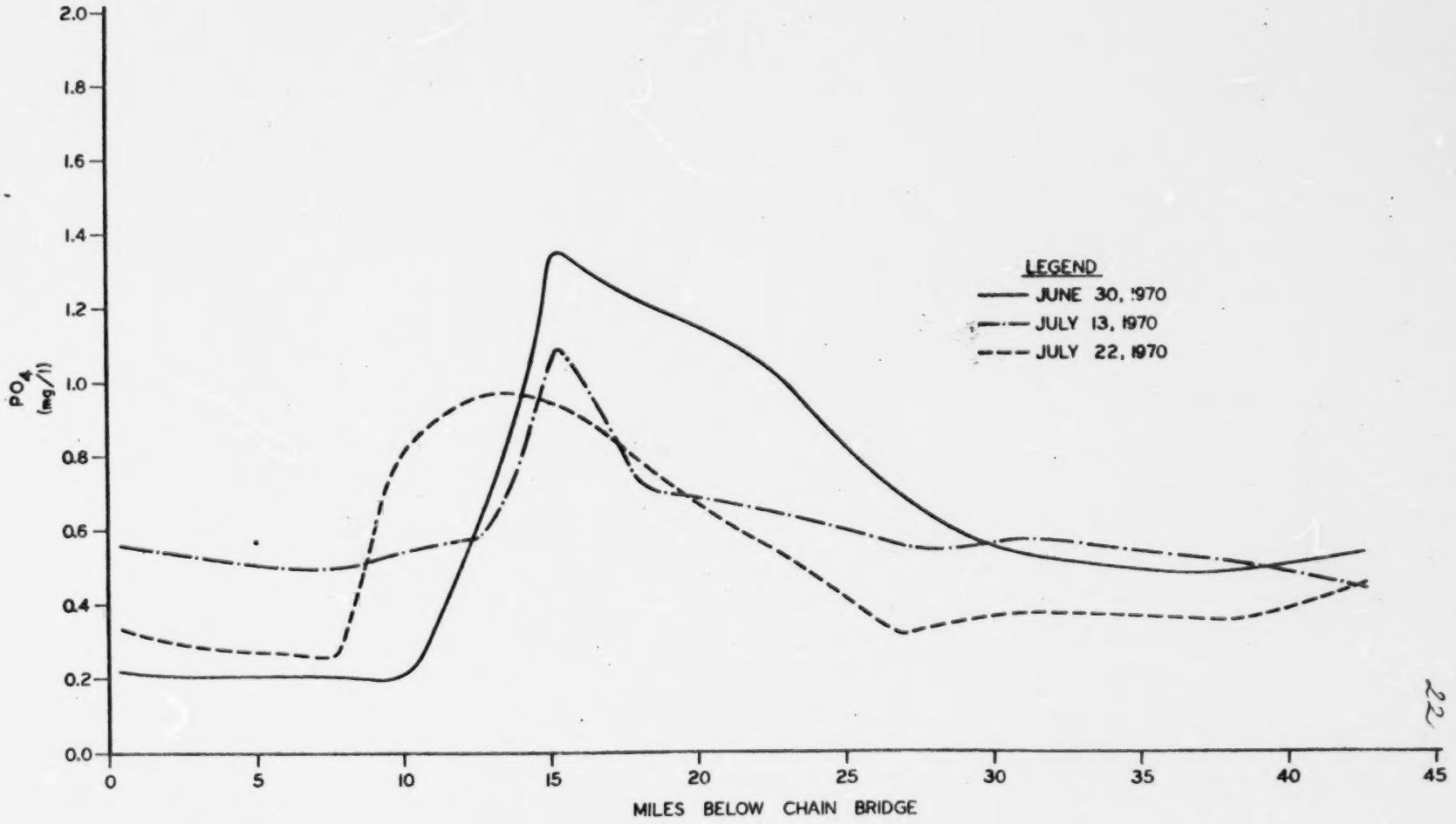

PHOSPHORUS CONCENTRATION
POTOMAC ESTUARY
LEGEND
JUNE 30, 1970
JULY 13, 1970
JULY 22, 1970
PO4 (mg/l)
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
5
10
15
20
25
30
35
40
45
MILES BELOW CHAIN BRIDGE

FIGURE 8

upper estuary. During the months of June through October, when blue-green algal growths become a nuisance, the contribution from the upper basin is small when compared to that from wastewater discharges (See Table 1).

Based on data as presented in Table 1, the amount of atmospheric nitrogen from rainfall, dustfall, and fixation by algae is approximately 1,600 lbs/day for the upper and middle Potomac Estuary. Extension of recent data from studies at the University of Wisconsin [31] indicate that approximately 5,000 lbs/day of nitrogen could be fixed by blue-green algae in the upper and middle reaches of the Potomac Estuary. Nevertheless, compared to all other sources, the contribution from the atmosphere including that by nitrogen fixing algae appears to be insignificant. Thus, during the summer months, algal control by management of nitrogen appears to be a feasible alternative to phosphorus control.

Under summer flow conditions, the alkalinity in runoff from the upper basin ranges from 80 to 100 mg/l, with wastewater discharges ranging from 100 to 150 mg/l. Including runoff and wastewater discharge sources only, approximately 60 to 70 percent of the total carbon entering the upper estuary is in the inorganic form.

Using only 0.1 percent of the transfer rate, the amount of carbon (CO_2) potentially available from the atmosphere is approximately 950,000 lbs/day (Table 1). With the upper reach of the estuary well

mixed due to tidal action, recruitment of carbon from benthic decomposition also appears to be another significant source of inorganic carbon.

Data indicate that waters of the lower reach of the Potomac Estuary and Chesapeake Bay are high in alkalinity and inorganic carbon. As the salt wedge moves upstream, there appears to be some recruitment of alkalinity and inorganic carbon from the Chesapeake Bay into the lower and middle reaches of the Potomac Estuary [17]. When all potential sources are considered, it appears that the management of carbon for algal control is not a feasible alternative at the present time.

NUTRIENT TRANSPORT AND ALGAL STANDING CROP MATHEMATICAL MODELS

In investigating the role of nitrogen and phosphorus on the eutrophic conditions in the Potomac Estuary, a detailed study of the movement of these nutrients was made using a "real time" dynamic water quality estuary mathematical model [10]. Models were also developed for algal standing crops and dissolved oxygen.

Phosphorus movement in the estuary was simulated by using a deposition formulation based on second order reaction kinetics. As shown in Figures 9 and 10, the model accurately predicts the rate of phosphorus deposition. Figure 11 indicates that the deposition rate is greatly affected by temperature. Analyses of the bottom muds of the estuary also indicate that large quantities of phosphorus are being lost to sediments in the vicinity of the wastewater discharges.

To determine if the phosphorus loss is related to algal growths, algal standing crops were predicted using a surrogate phosphorus mathematical model. In the model, the loss in phosphorus was converted to algal standing crops using a chlorophyll a/phosphorus weight relationship as given in Table 2. Based on six simulated standing crop studies, it appears that only 10 to 30 percent of the phosphorus losses from the aqueous system can be accounted for by uptake of algal cells.

In investigating the role of nitrogen in water quality management, a feedback system of the nitrogen cycle was incorporated into the dynamic estuary mathematical model similar to that proposed by Thomann *et al* [29]. The model, as shown in Figure 12, consists of six possible

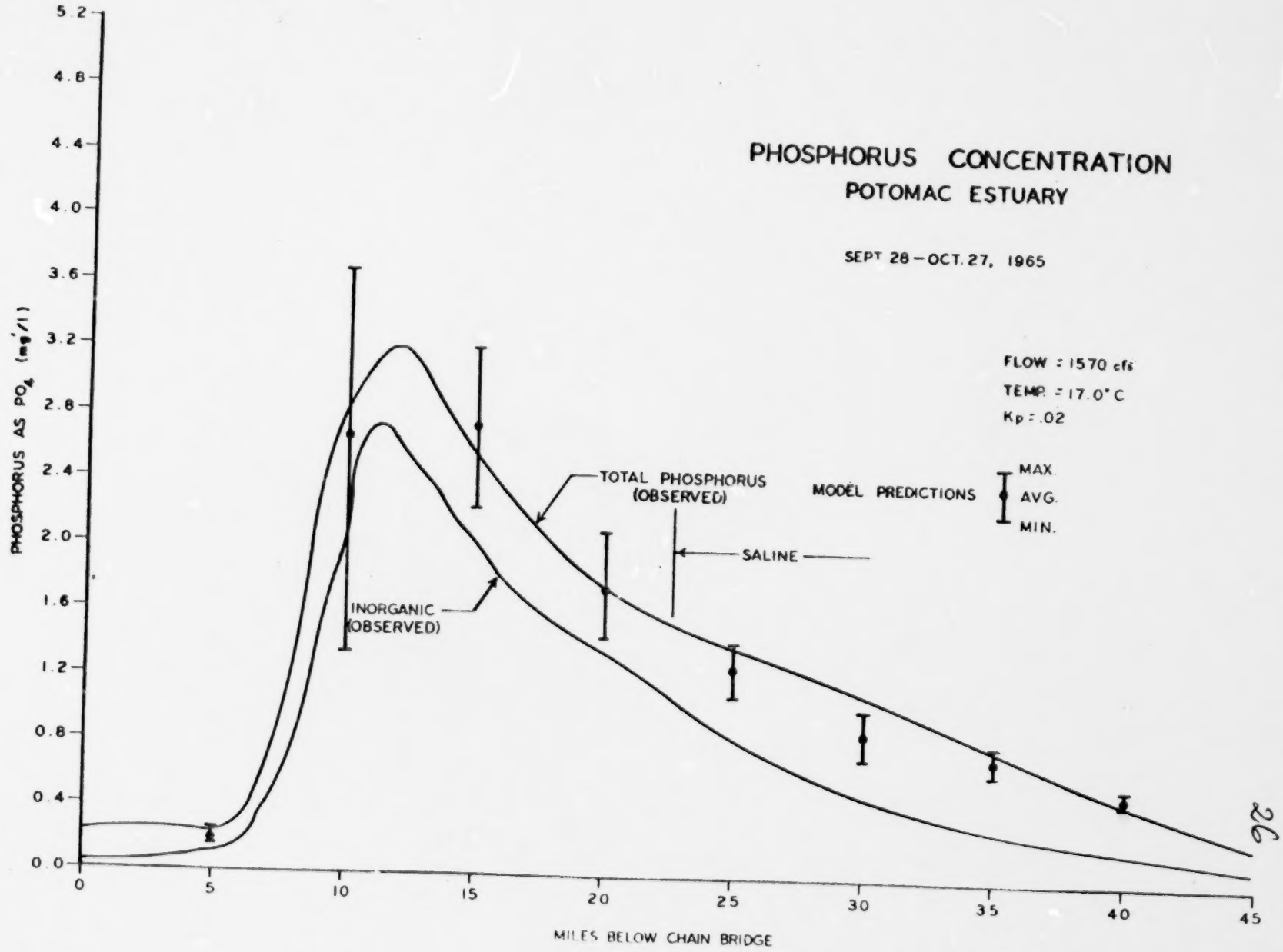

PHOSPHORUS CONCENTRATION
POTOMAC ESTUARY
SEPT 28 – OCT. 27, 1965
FLOW = 1570 cfs
TEMP. = 17.0° C
Kp = .02
TOTAL PHOSPHORUS (OBSERVED)
MODEL PREDICTIONS
MAX.
AVG.
MIN.
SALINE
INORGANIC (OBSERVED)
PHOSPHORUS AS PO_4 (mg/l)
MILES BELOW CHAIN BRIDGE
5.2
4.8
4.4
4.0
3.6
3.2
2.8
2.4
2.0
1.6
1.2
0.8
0.4
0.0
0
5
10
15
20
25
30
35
40
45

FIGURE 9

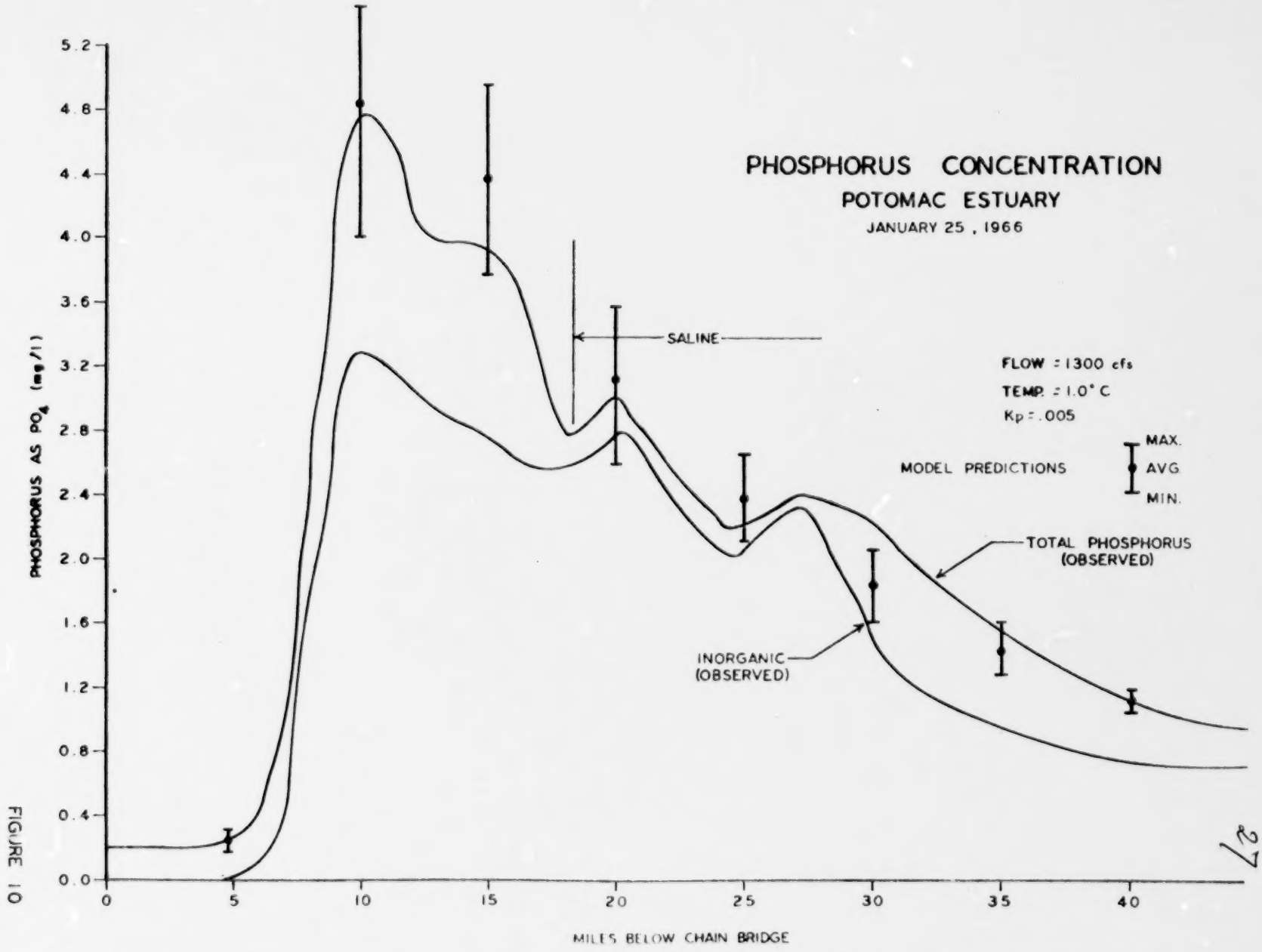
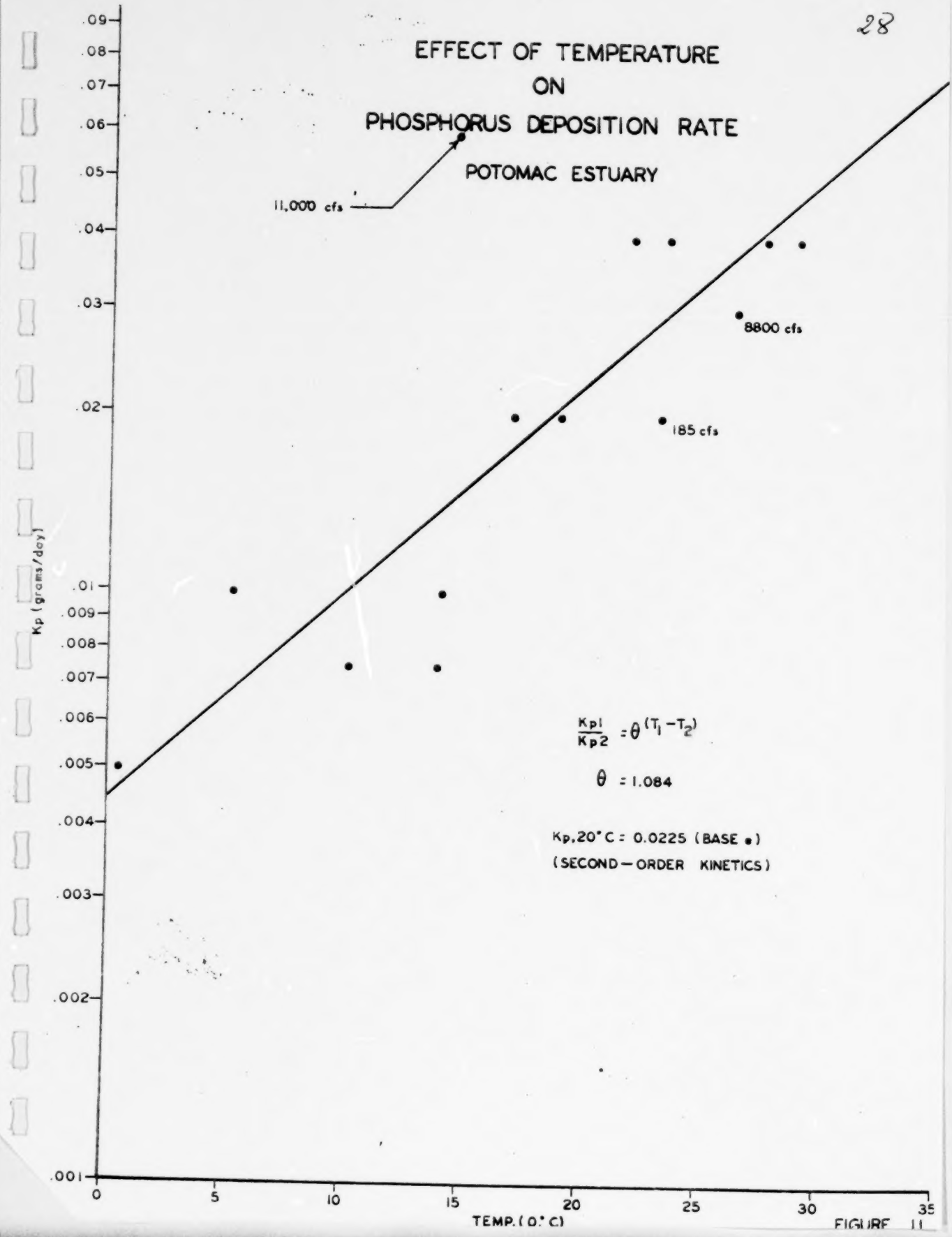

PHOSPHORUS CONCENTRATION
POTOMAC ESTUARY
JANUARY 25 , 1966
PHOSPHORUS AS PO_4 (mg/l)
MILES BELOW CHAIN BRIDGE
SALINE
FLOW = 1300 cfs
TEMP. = 1.0° C
Kp = .005
MODEL PREDICTIONS
MAX.
AVG.
MIN.
TOTAL PHOSPHORUS (OBSERVED)
INORGANIC (OBSERVED)
5.2
4.8
4.4
4.0
3.6
3.2
2.8
2.4
2.0
1.6
1.2
0.8
0.4
0.0
0
5
10
15
20
25
30
35
40

FIGURE 10

EFFECT OF TEMPERATURE ON PHOSPHORUS DEPOSITION RATE

POTOMAC ESTUARY



$$\frac{Kp1}{Kp2} = \theta^{(T_1 - T_2)}$$

$\theta = 1.084$

Kp, 20° C = 0.0225 (BASE e)

(SECOND – ORDER KINETICS)

FIGURE 11

reactions: (1) chemical and biological decomposition of organic nitrogen to ammonia, (2) bacterial nitrification of ammonia to nitrite and nitrate, (3) phytoplankton utilization of ammonia, (4) phytoplankton utilization of nitrite and nitrate, (5) deposition of organic nitrogen, and (6) the death of the phytoplankton. With the area near Woodrow Wilson Bridge being light limited with respect to algal growths, the rate of phytoplankton utilization of ammonia appears to be less than that in the area near Indian Head.

For summer temperatures of 26°C to 29°C, first-order kinetic reaction rates have been established for the various processes given below:

Nitrification by bacteria	0.30 to 0.40
Nitrogen utilization by phytoplankton	0.07 to 0.09
Deposition of algal cells	0.005 to 0.05

The first two processes (nitrification and nitrogen utilization) including the reaction rates have been well established as shown in the predicted profiles (Figures 13 and 14). The effect of temperature on the nitrification process and the rate of nitrogen utilization by algal cells has also been formulated as shown in Figures 15 and 16.

Initial simulations indicate that the rate of recycling of nitrogen was not significant in the freshwater portions. As can be seen in Figures 13 and 14, there is a discontinuity in the nitrogen cycle at the point of saline intrusion. This discontinuity appears to be a result of the transformation from fresh to mesohaline organisms. It appears that

the rate of decomposition of organic nitrogen is much slower than the rate of bacterial nitrification or the rate of nitrogen uptake by algal cells in that the predominant form of nitrogen in the middle and lower estuaries is organic.

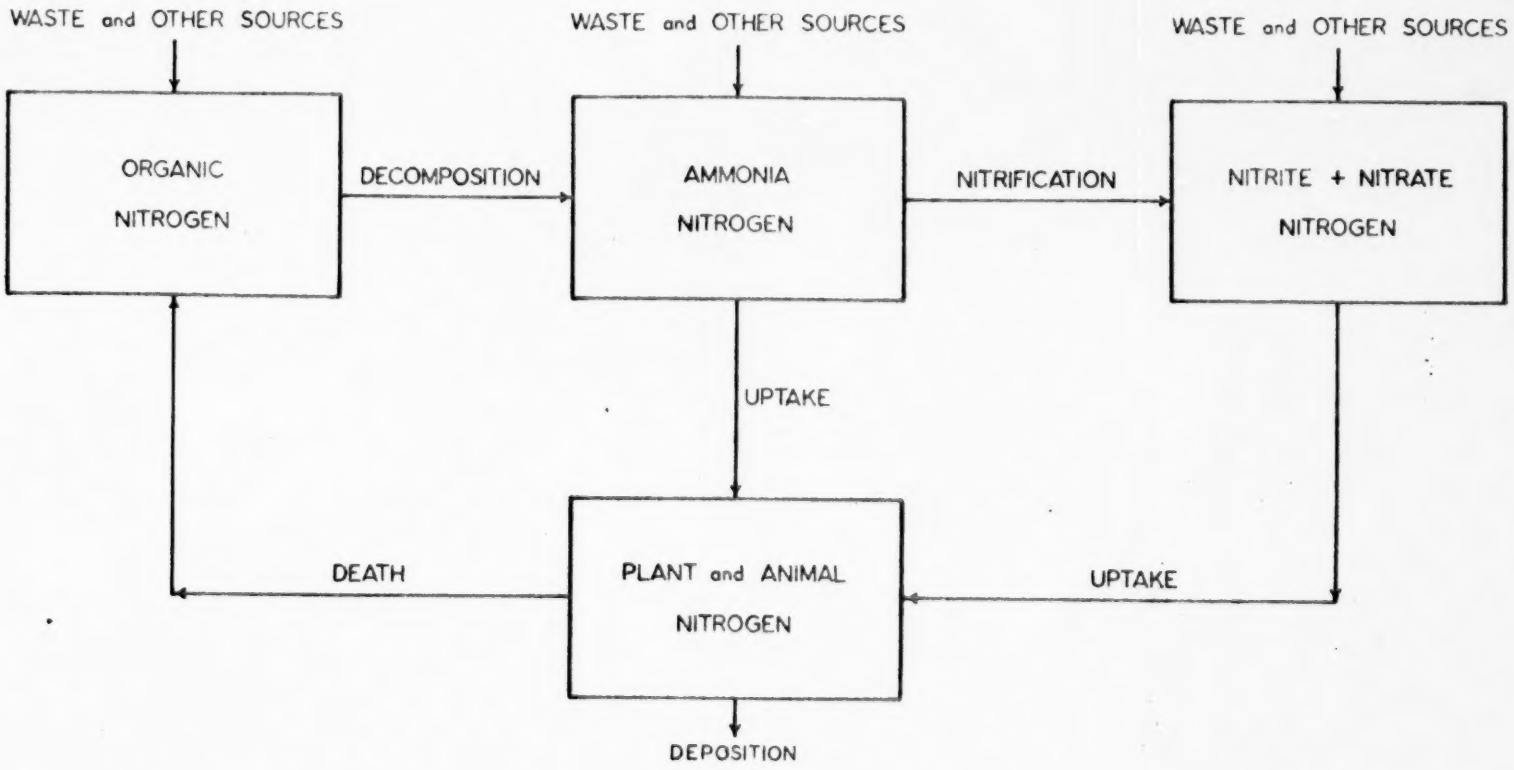
Table 2

DATA SUMMARY OF

ALGAL CHEMICAL COMPOSITION STUDIES

Potomac Estuary
June - October 1970

Nutrient	mg. of Nutrient / ug of Chlorophyll a	mg. of Nutrient / mg. of S. Solids
Carbon	0.045	0.331
Nitrogen	0.010	0.073
Phosphorus	0.001	0.006



SIMPLIFIED NITROGEN CYCLE

FIGURE 12

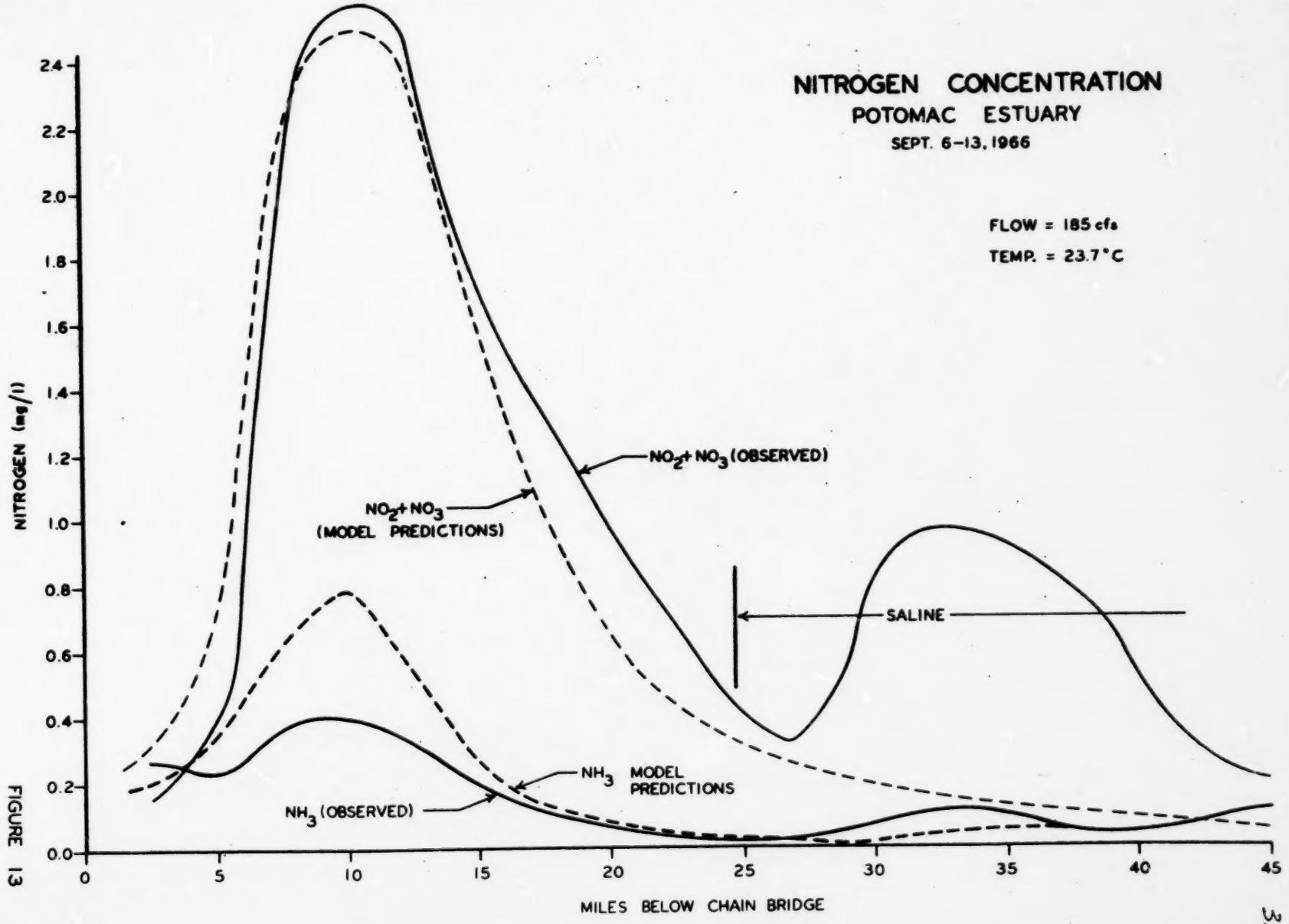
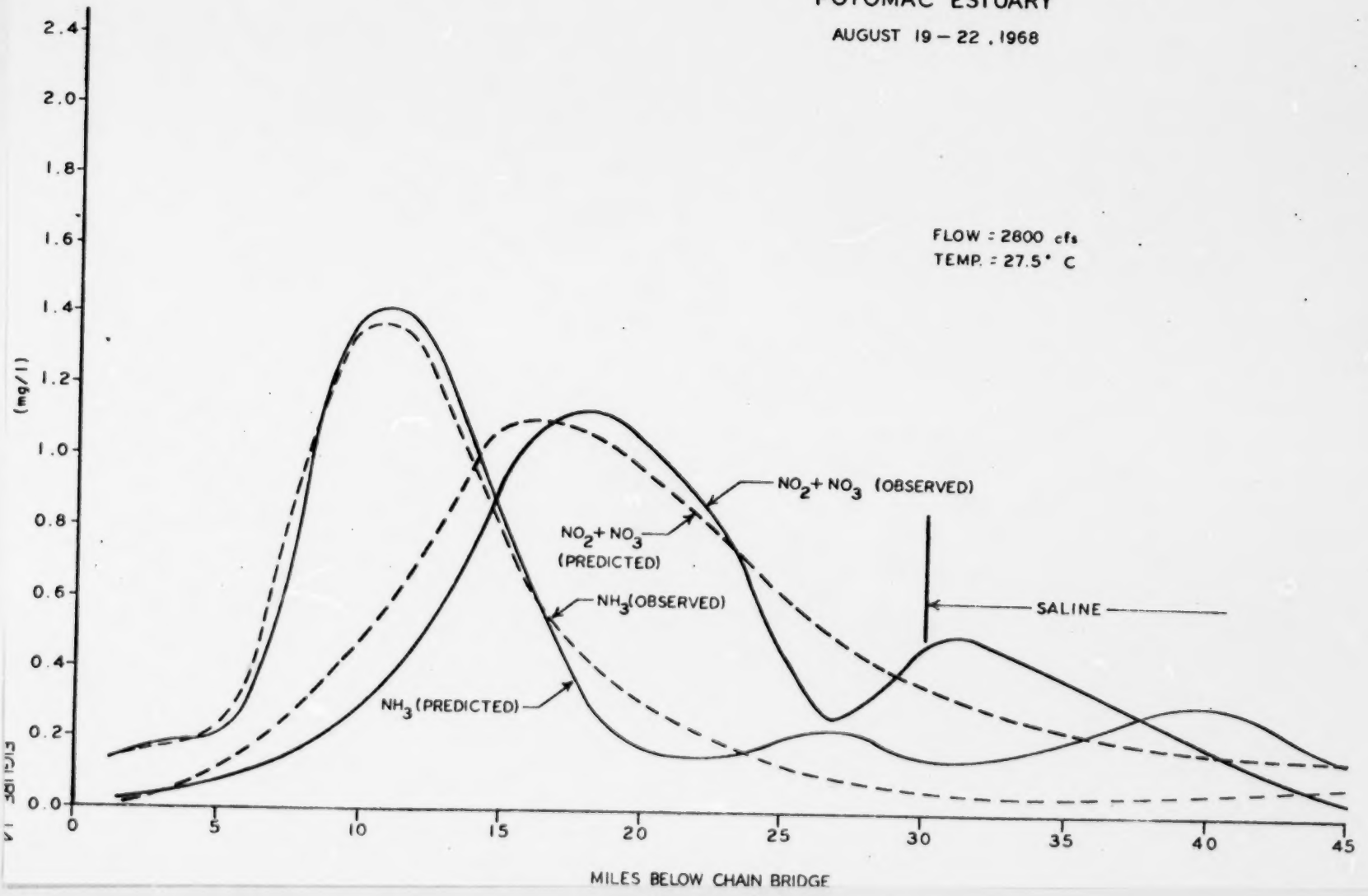

NITROGEN CONCENTRATION
POTOMAC ESTUARY
SEPT. 6-13, 1966
FLOW = 185 cfs
TEMP. = 23.7°C
NITROGEN (mg/l)
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
5
10
15
20
25
30
35
40
45
MILES BELOW CHAIN BRIDGE
NO2+NO3 (OBSERVED)
NO2+NO3 (MODEL PREDICTIONS)
SALINE
NH3 MODEL PREDICTIONS
NH3 (OBSERVED)

FIGURE 13

NITROGEN CONCENTRATION
POTOMAC ESTUARY
AUGUST 19 – 22 , 1968



EFFECT OF TEMPERATURE ON NITRIFICATION RATE

POTOMAC ESTUARY

$NH_3 \longrightarrow NO_2 + NO_3$

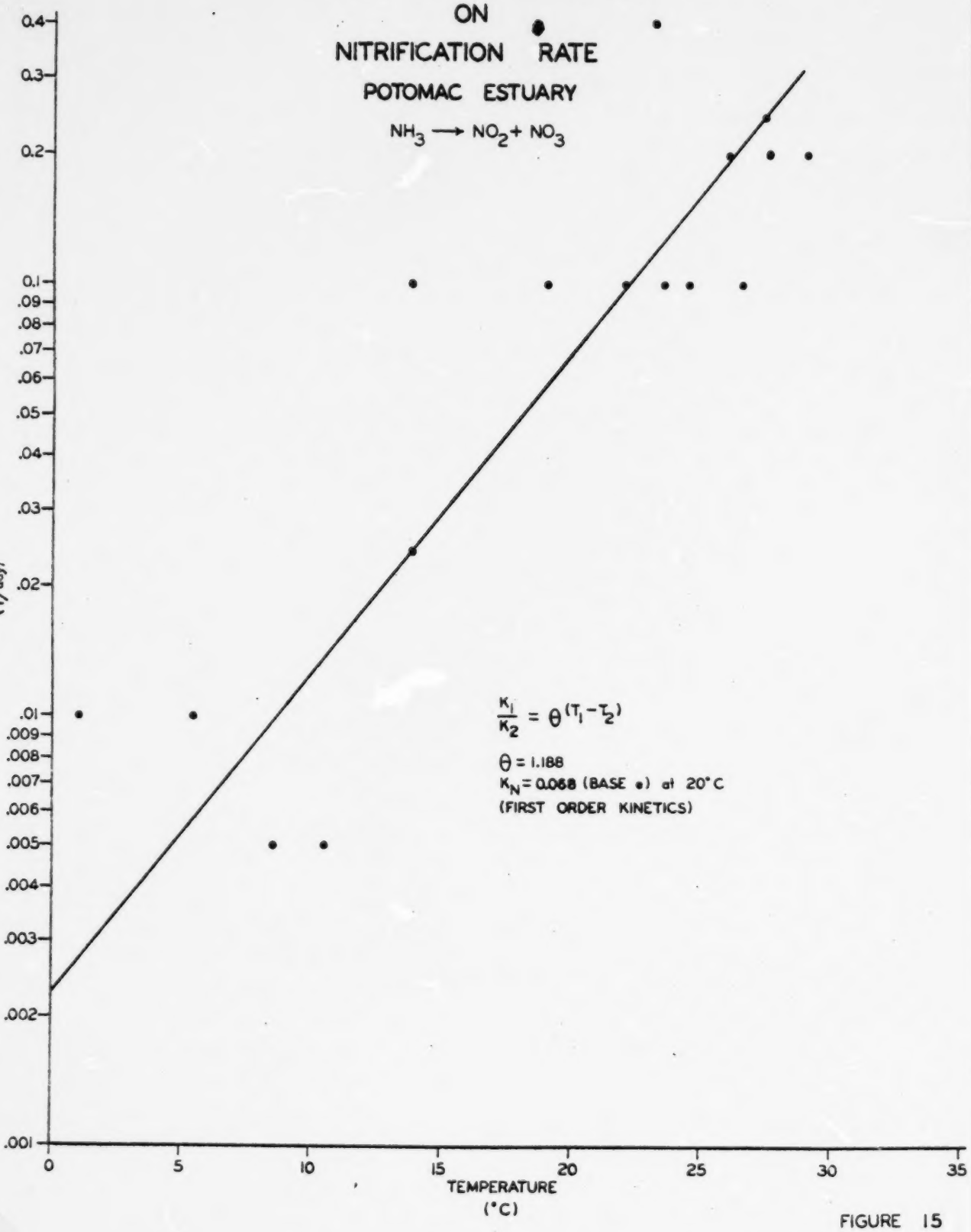


FIGURE 15

EFFECT OF TEMPERATURE ON RATE OF NITROGEN UTILIZATION BY ALGAE

POTOMAC ESTUARY

$NO_3 \longrightarrow$ ALGAL NITROGEN

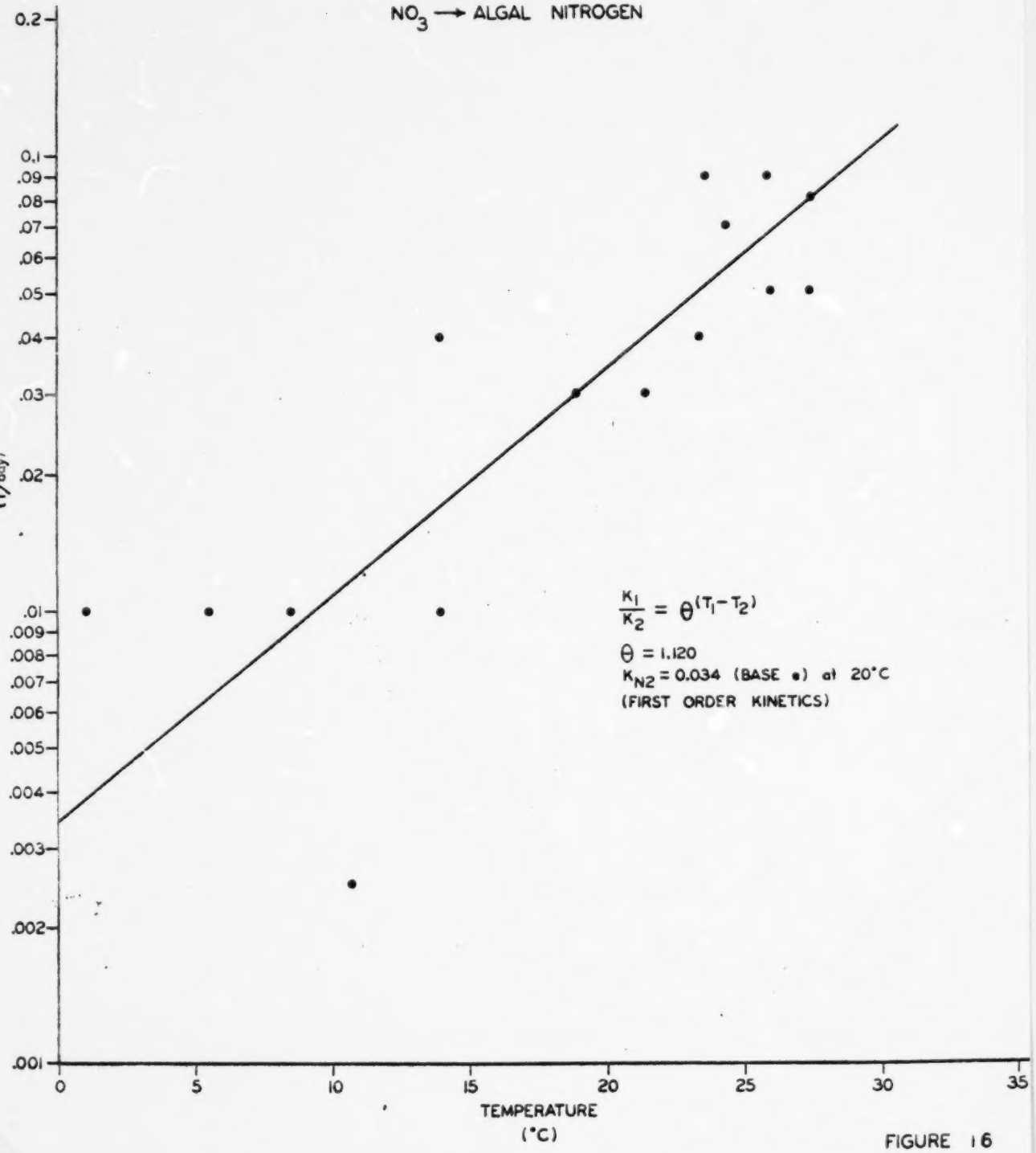


FIGURE 16

Using the weight ratio of nitrogen to chlorophyll a (Table 2) and the nitrogen model rates indicated above, the dynamic model was expanded to predict the concentration of chlorophyll a based on the utilization of inorganic nitrogen. In Figures 17 and 18, predicted profiles using the surrogate algal model and observed data are presented. The predicted maximum concentrations compare closely to the observed data in both distribution and magnitude. Eight other model predictions have been made and will be described fully in a report currently being prepared by CTSL.

A DO budget has been incorporated into the dynamic water quality model consisting of the following five linkages:

(1) Oxidation of carbonaceous matter,

(2) Oxidation of nitrogenous matter (ammonia and organic),

(3) Oxygen production and respiration of simulated algal standing crops based upon the nitrogen cycle,

(4) Benthic demand, and

(5) Reaeration from the atmosphere.

The model, which is also described in the CTSL report currently in preparation, has been verified for flow ranges from 212 to 8800 cfs. The average observed and predicted DO concentrations for the periods of September 22, 1968, and August 12-19, 1969, (Figures 19 and 20 respectively) demonstrate that the model can predict DO responses over a wide range of freshwater inflows.

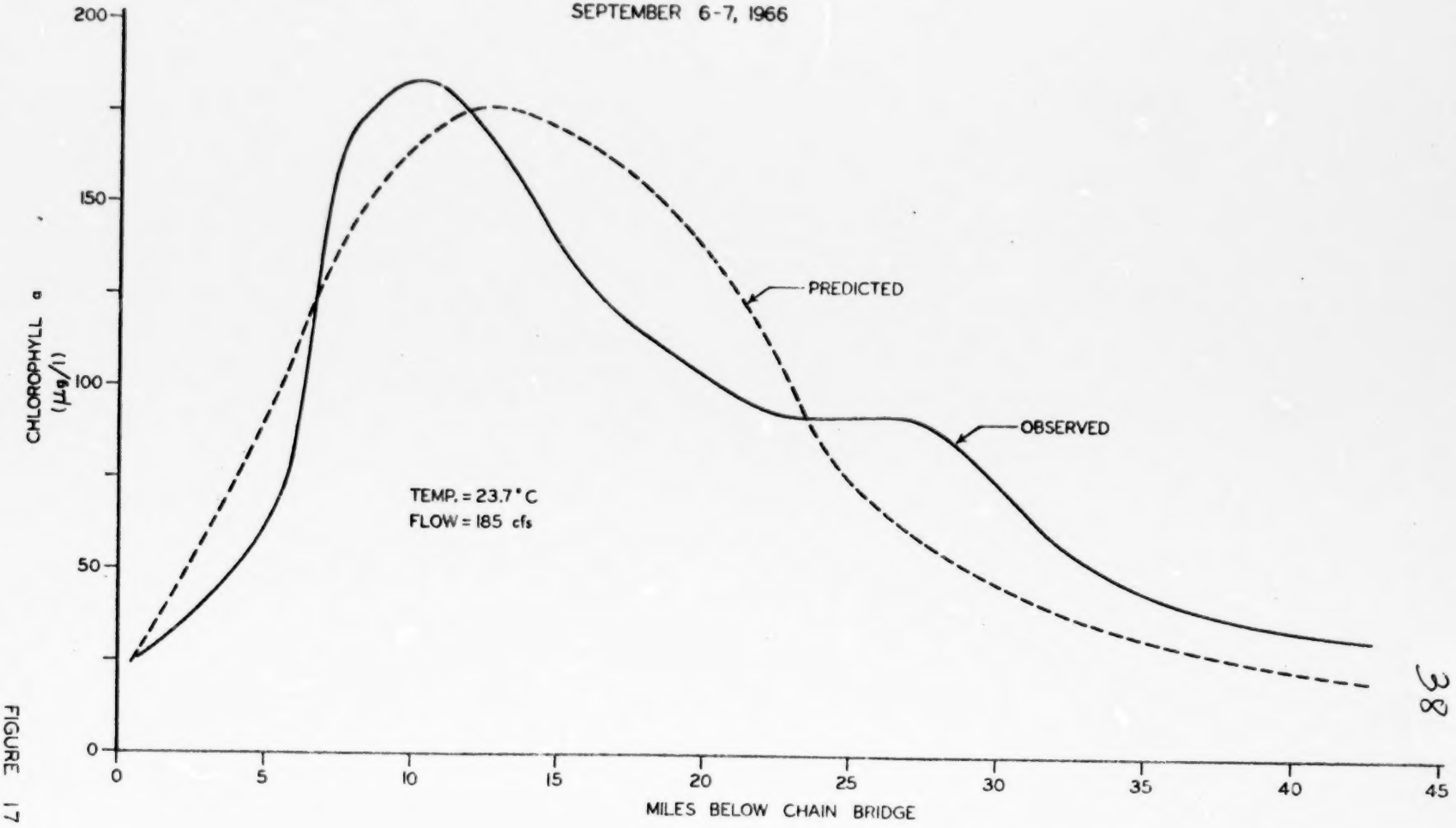

CHLOROPHYLL CONCENTRATION
POTOMAC ESTUARY
SEPTEMBER 6-7, 1966
CHLOROPHYLL a (µg/l)
200
150
100
50
0
PREDICTED
OBSERVED
TEMP. = 23.7 °C
FLOW = 185 cfs
0
5
10
15
20
25
30
35
40
45
MILES BELOW CHAIN BRIDGE

FIGURE 17

CHLOROPHYLL CONCENTRATION

POTOMAC ESTUARY

AUGUST 19-23, 1968

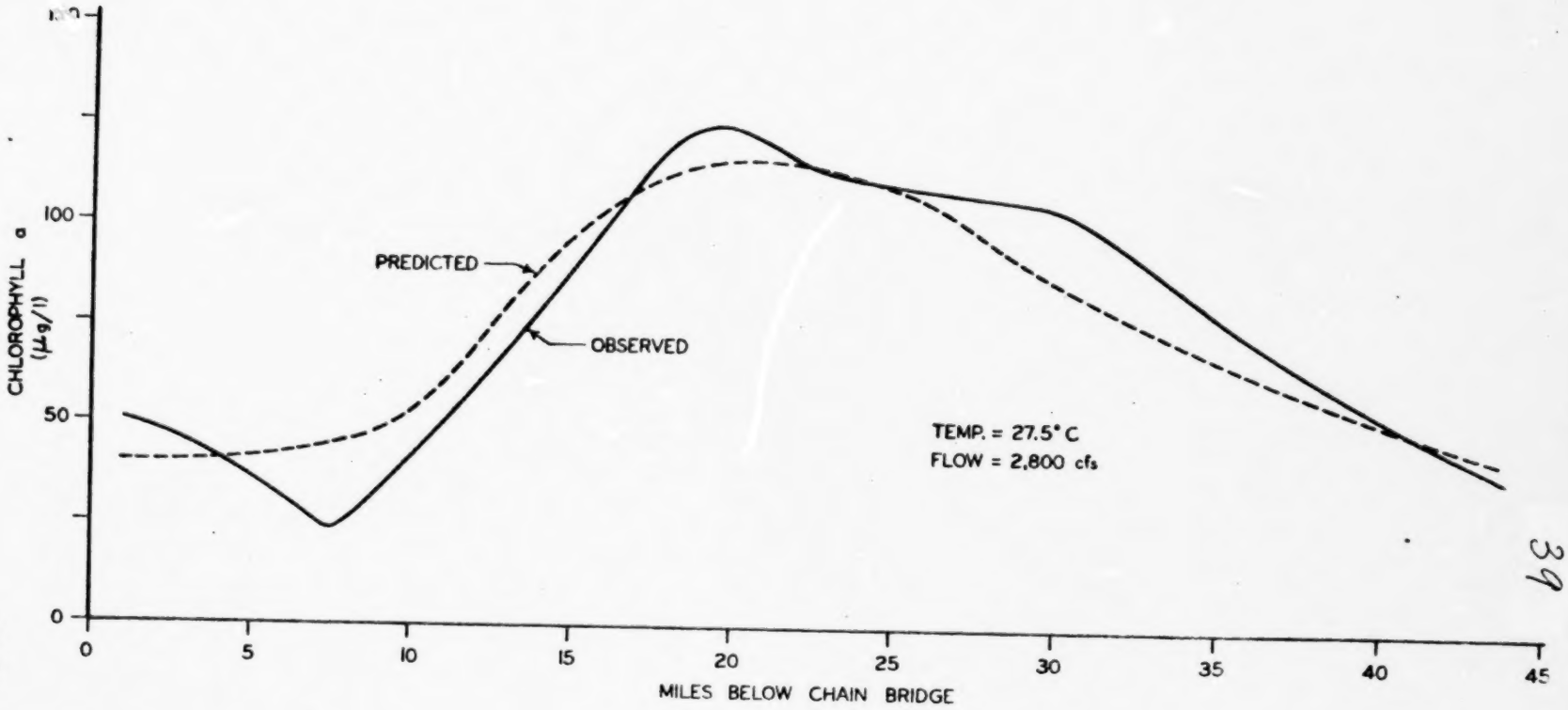


FIGURE 18

DO CONCENTRATIONS

POTOMAC ESTUARY

SEPT. 22, 1968

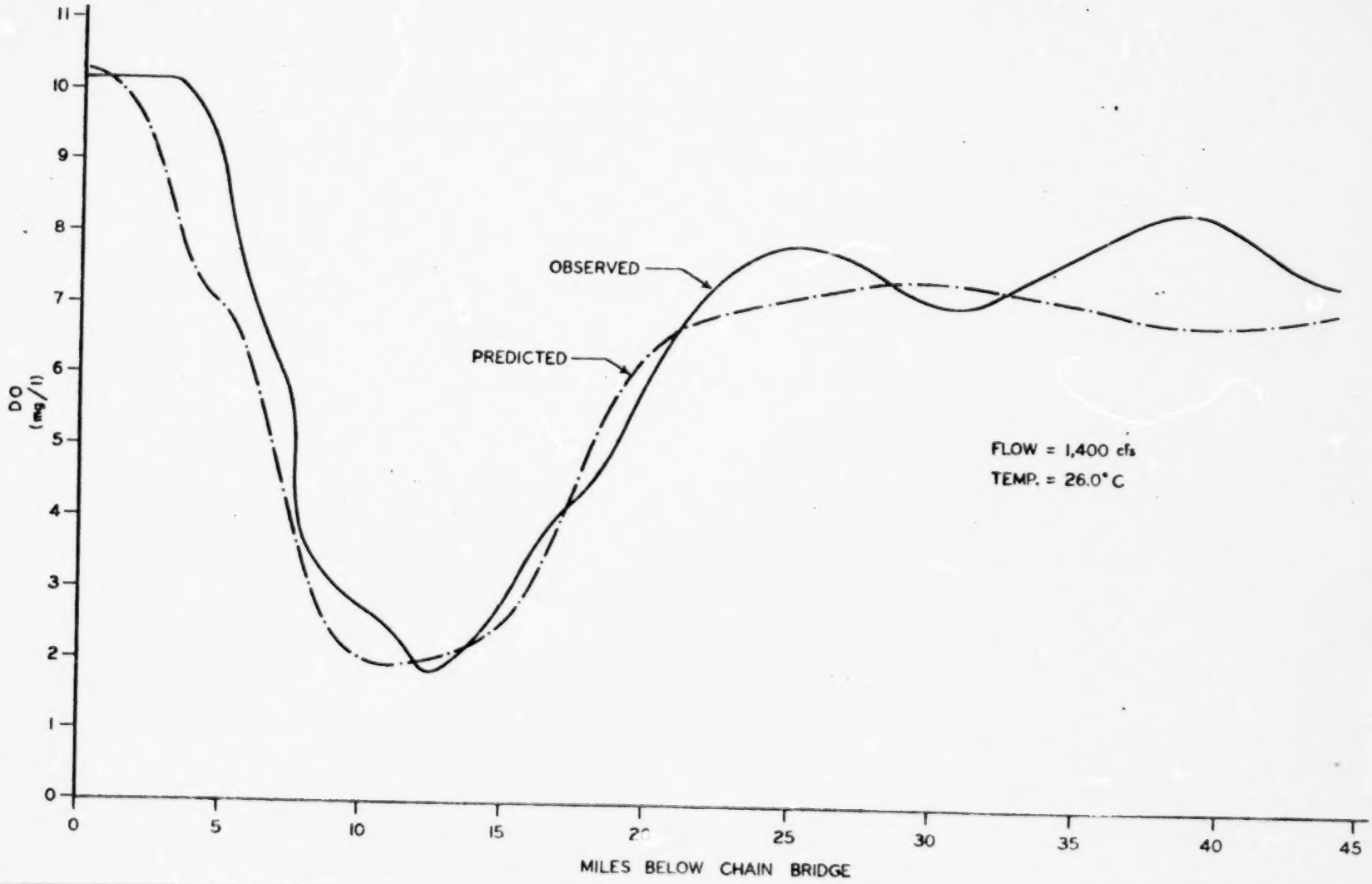


FIGURE 19

DO CONCENTRATIONS

POTOMAC ESTUARY

AUG. 12-17, 1969

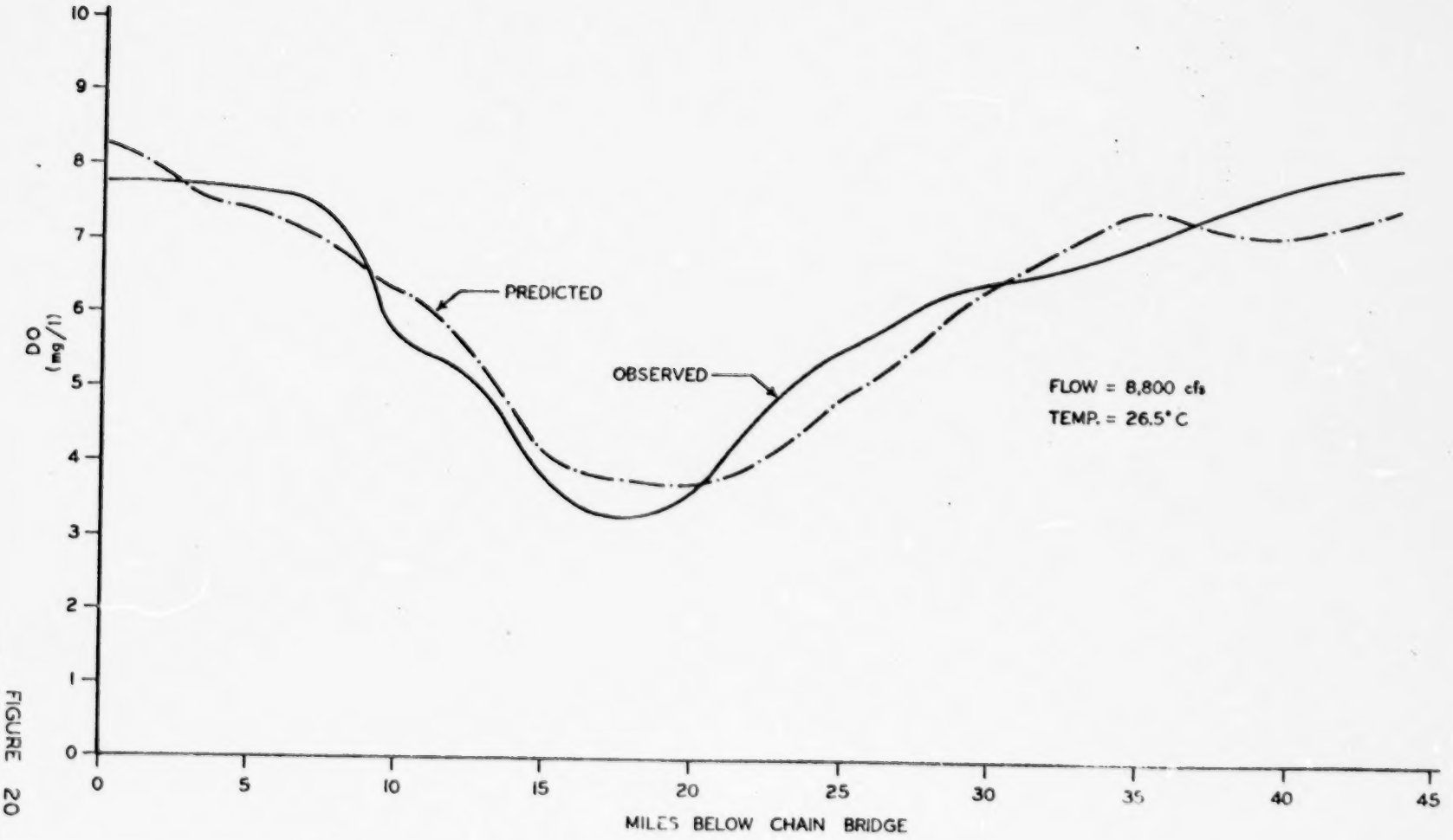


FIGURE 20

The basic coefficients used in the DO budget model were:

Process	Rate (base e) at 20°C	Temperature Coefficient θ $(T1 - T20)$
Carbonaceous oxidation	0.230	1.047
Nitrogenous oxidation	0.068	1.188
Algal utilization of nitrogen	0.034	1.120
Reaeration from the atmosphere	*	1.021

The remaining processes in the DO budget are given below:

Algal oxygen production rate = 0.012 mg O_2/hr/ug chlorophyll a

Algal respiration rate = 0.008 mg O_2/hr/ug chlorophyll a

Euphotic zone = 2 feet

Respiration depth = full depth of water column

Algal oxygen production period = 12 hours

Algal respiration period = 24 hours

Benthic demand rate = 1.0 gr O_2/day sq meter

The five linkages provide a mechanism for not only investigating the effects of the various components on the dissolved oxygen budget but also for establishing the algal standing crop limits and nutrient criteria.

* Based on a velocity and depth formulation

EUTROPHICATION CONTROL

For purposes of water quality management, the upper Potomac Estuary may be considered eutrophic when undesired standing crops become the predominant plant life as is now occurring with the nuisance blue-green alga species. The major objectives for controlling the blue-green algal standing crop in the upper estuary are fourfold:

1. To reduce the dissolved oxygen (DO) depression caused by respiration and the decay of algal growths especially in waters over 10 feet in depth. At times, DO depressions of more than 3.0 mg/l below saturation occur even during daylight hours.

2. To minimize the increase of ultimate oxygen demand which is a result of the conversion of inorganic carbon and nitrogen to oxidizable organic compounds by algal cells. Currently, more UOD is added to the upper Potomac Estuary in the summer months as a result of algal growth than from wastewater discharges.

3. To enhance the aesthetic condi- n the upper estuary. Large green mats develop during the months of ough October and create objectionable odors, clog marinas, cover beaches and shorelines, and in general reduce the potential of the estuary for recreational purposes such as fishing, boating, and water skiing.

4. To reduce any potential toxin problem and objectionable taste and odors caused by blue-green algae if the upper estuary is to be used as a supplemental water supply.

To aid in defining an algal standing crop limit, a subjective analysis using chlorophyll concentrations was developed incorporating conditions having possible effects on water quality. Four major interferences are offered in this analysis (Table 3) including the desired reduction in the chlorophyll standing crop for each of the parameters.

The desired maximum limit of 0.5 mg/l DO below saturation was set to allow for assimilation of waste discharges and naturally occurring oxygen demanding pollutants. To minimize the effects of increased organic loads and sludge deposits caused by algal growths, an upper limit of 5.0 mg/l of total oxygen demand is proposed.

Of the four interferences, the most stringent reduction percentage is in the control of growths to prevent nuisance conditions. From the above analysis, a 75 to 90 percent reduction in chlorophyll concentration will be required in the Potomac Estuary, or chlorophyll levels of approximately 25 ug/l.

Table 3

SUBJECTIVE ANALYSIS OF ALGAL CONTROL REQUIREMENTS

Water Quality or Water Use Interference	Indications of Interference	Magnitude of Current Interference*	Desired Limit	Required Percentage Reduction of Current Standing Crop
DO Depression Caused by Decay and Respiration	mg/l of DO Below Saturation	1.5 to 3.0 mg/l	0.5 mg/l	65-85
Increase in Total Oxygen Demanding Load	mg/l of Increase in Ultimate BOD	15 to 30 mg/l	5.0 mg/l	65-80
Recreational & Aesthetic Nuisance Conditions	Chlorophyll Concentration	100 to >250 ug/l	25 ug/l**	75-90
Toxins, Taste, & Odor	Undefined	Unknown	Unknown	Unknown

* Under nuisance bloom conditions, chlorophyll concentrations range from 100 to >250 ug/l

** Average over entire water column

ESTABLISHMENT OF NUTRIENT CRITERIA

Various investigators studying algal growth requirements have discussed the concentrations of nitrogen and phosphorus needed to stimulate algal blooms. In a recent study of the Occoquan Reservoir, located on a tributary of the Potomac Estuary, Sawyer [27] recommended limits of inorganic nitrogen and inorganic phosphorus of 0.35 and 0.02, respectively. Mackenthun [24] cites data indicating upper limits of inorganic nitrogen at 0.3 mg/l and inorganic phosphorus at 0.01 mg/l at the start of the growing season to prevent blooms. FWQA's Committee on Water Quality Criteria recommends an upper limit of 0.05 mg/l of total phosphorus for estuarine waters [9]. No recommendations for inorganic nitrogen were presented other than that the naturally occurring ratio of nitrogen to phosphorus should not be radically changed.

Pritchard [25], studying the Chesapeake Bay and its tributaries, suggests that if total phosphorus concentrations in estuarine waters are below 0.03 mg/l, biologically healthy conditions will be maintained. Pritchard suggested no limit for nitrogen. Jaworski et al [16], reviewing historical data for the upper Potomac Estuary, indicated that if the concentrations of inorganic phosphorus and inorganic nitrogen were at or above 0.1 and 0.5, respectively, algal blooms of approximately 50 ug/l would result. Chlorophyll a of 50 ug/l or over was considered indicative of excessive algal growths. Studies of the James River Estuary, a sister estuary to the Potomac, by Brehmer and Haltiwanger [4] indicate that nitrogen appears to be the rate limiting nutrient.

Recently, the management of carbon in controlling algal blooms has been suggested by Kuentzel [20] and Lange [21]. Studies by Kerr et al [19] also suggest that inorganic carbon is apparently directly responsible for increased algal populations in waters that they have studied. The Kerr studies indicate that the addition of nitrogen and phosphorus indirectly increases algal growth by stimulating growth of large heterotrophic bacterial populations. No criteria for nitrogen, phosphorus, or carbon were indicated by Kerr.

In addition to the data reviewed above and that cited by numerous investigators not reported, six methods were used to develop the nutrient requirements for the Potomac Estuary. The six were:

1. Algal chemical composition analyses,
2. Analysis of the nutrient data on an annual cycle and profile basis,
3. Nutrient bioassay,
4. Nutrient and algal mathematical modeling,
5. Comparison with an estuary currently not eutrophic, and
6. Review of historical nutrient and ecological trends in the Potomac Estuary.

1. Algal Composition Analysis

An analysis of the chemical composition of blue-green algae in the Potomac was made during the summer months of 1970. Summary data in terms of micrograms of chlorophyll a and grams of suspended solids are presented in Table 2.

Based on data in Table 2, an algal bloom of 100 ug/l chlorophyll a contains the following:

Parameter	Concentration
S. Solids	14.2 mg/l
Carbon	4.5 mg/l
Nitrogen	1.0 mg/l
Phosphorus	0.1 mg/l

For the Potomac Estuary, which can be considered a slow-moving continuous culture system, concentrations equal to or less than 1.12 mg/l of carbon, 0.25 mg/l of nitrogen, and .025 mg/l of phosphorus would be theoretically required to maintain a 25 ug/l chlorophyll a level. Upper limits of nutrients using this method should be considered minimal concentrations, since no loss to sediments is assumed.

2. Analysis of Data on an Annual Cycle and Longitudinal Profile Basis

Nutrients not removed from the waters are still capable of supporting the growth of algae and other organisms if there is an adequate supply of the remaining nutrients in the smallest quantity needed for growth. Using the disappearance of a specific nutrient both seasonally and along longitudinal profiles, insight can be gained as to the possibility that the nutrient is limiting algal growth. This assumes that other environmental factors do not restrict growth.

From Indian Head to Smith Point, which is the area of pronounced algal growth, there is over 0.15 mg/l of phosphorus in the waters even under maximum bloom conditions. (In Figure 2, inorganic phosphorus

concentrations are given.) Data indicated that in the upper and middle reaches of the Potomac, phosphorus is in excess and thus is not rate limiting. In the lower reach near Piney Point, the total phosphorus concentration is often 0.04 mg/l and thus phosphorus could be limiting for this reach.

When the NO_2 + NO_3 and NH_3 concentrations shown in Figures 3 and 4 are reviewed, it is evident that practically all of the inorganic nitrogen had disappeared in the reach between the Smith Point and Route 301 Bridge stations by late July 1969 and by mid-August 1970. This depletion occurred even though the summers of 1969 and 1970 had relatively high flows. Based upon the disappearance of inorganic nitrogen, it appears that nitrogen becomes a major factor in limiting algal growth in the middle and lower estuary.

To determine if carbon was limiting algal growth in the bloom area of the Potomac Estuary, a review of historical alkalinity data was made. Total and inorganic carbon analyses were also conducted during the latter part of 1969 and throughout 1970.

During August and September 1970, river flows were low with air temperatures reaching 95°F during most of the days in September. Dense algal blooms extended from Hains Point to Smith Point. Carbon

concentrations obtained during a sampling cruise on September 20, 1970, were as follows:

Station	Organic Carbon (mg/l)	Inorganic Carbon (mg/l)
Hains Point	7.2	12.2
Wilson Bridge	10.2	15.4
Piscataway	10.5	8.6
Indian Head	10.5	15.0
Smith Point	8.5	7.7
Route 301 Bridge	6.1	6.1

The above data obtained during the mid-day hours of September 20, 1970, indicate that large quantities of inorganic carbon were available for algal growth even during periods of dense blooms. The 1969 data, historical alkalinity data, and other 1970 cruise data also substantiate the September 1970 findings.

3. Bioassay Studies

To determine further what nutrients were limiting algal growth in the Potomac, bioassay tests as developed by Fitzgerald [11] [12] were employed. Tests for both phosphorus and nitrogen were conducted in the Potomac from Piscataway Creek to Route 301 Bridge for the period June through October 1970.

Using the rate of ammonia absorption by algal growths, it is possible to determine if the algal cells have surplus nitrogen or if they are nitrogen starved. Tests made during June and early July indicate that ammonia was either released or absorbed at a low rate

in the range of 10^{-6} mg N/hr/ug chlorophyll a. The cells had adequate nitrogen available for growth as was also indicated by the high nitrate concentration in the water, especially at the upper stations above Indian Head.

Tests for the latter part of July and August exhibited rates of absorption that were approximately twice as high for the Indian Head station as for the lower station at Maryland Point. In addition, when compared to the earlier data, the absorption rates were considerably higher ranging in the area of 10^{-4} mg N/hr/ug chlorophyll a.

Bioassay tests for October 13, 1970, as tabulated below, show a significant increase in ammonia absorption rates between the Piscataway station and the Smith Point station farther downstream.

Station	NH_3 In Water (mg/l)	$NO_2 + NO_3$ In Water (mg/l)	Ammonia Nitrogen Absorbed (mg N/hr/ug chloro)
Piscataway	.110	2.560	$+ 6.0 \times 10^{-5}$
Indian Head	.150	.684	$+ 6.0 \times 10^{-5}$
Possum Point	.001	.220	$+ 2.3 \times 10^{-4}$
Smith Point	.001	.150	$+ 1.3 \times 10^{-4}$

The higher rates of ammonia absorption for Possum and Smith Points and the low concentration of inorganic nitrogen indicates that this reach of the Potomac is becoming nitrogen limited.

Two tests, an extraction procedure and an enzymatic analysis [12], were used to determine if algal growth was phosphorus limited. The phosphorus extraction bioassay studies indicated very little difference

between amounts of phosphorus released at the upstream and downstream stations. Tests for alkaline phosphatase, an enzyme indicator of phosphorus starved algal cells, were all negative. These two tests also confirmed the observation, discussed in the previous section, that the phosphorus content in the upper and middle estuary was excessive (over 0.15 mg/l as P).

4. Algal Modeling

Recognizing the possibility that the Potomac becomes nitrogen limited in late summer, a detailed investigation was made using the algal standing crop model previously described. From these mathematical model runs, it can be concluded that the standing crop of blue-green algae can be predicted using the nitrogen cycle. This further supports the premise that the availability of nitrogen appears to control the algal standing crop. Moreover, it appears that if the inorganic nitrogen is maintained between 0.2 and 0.4 mg/l, the standing crop can be reduced to the desired limit as indicated by a maximum chlorophyll a concentration of 25 ug/l.

5. Comparison with a Non-eutrophic Estuary

To investigate further the nutrient requirements for algal growth, a study was made of the upper Rappahannock Estuary (a sister estuary located south of the Potomac in the State of Virginia). During the summer months of 1970, seven sampling cruises were made of the upper 30 miles of the estuary which is non-eutrophic.

The freshwater portion of the estuary contains relatively high concentrations of both organic and inorganic carbon and low levels of nitrates and inorganic phosphorus as given below:

Nutrient	Average Concentration Ranges
Total phosphorus	.05 - .08 (mg/l)
Inorganic phosphorus	.03 - .07 (mg/l)
Inorganic nitrogen	.10 - .40 (mg/l)
Organic carbon	5.00 - 18.00 (mg/l)
Inorganic carbon	4.00 - 10.00 (mg/l)
Chlorophyll a	8.00 - 40.00 (ug/l)

An analysis of the data for the freshwater portion of the Rappahannock Estuary indicates that if the total phosphorus and nitrogen concentrations are less than 0.08 and 0.4 mg/l, respectively, the standing crop of algae (within the 25 ug/l of chlorophyll objective) can be maintained.

6. Review of Historical Nutrient and Ecological Trends in the Potomac Estuary

As reported earlier, there appears to be a definite relationship between ecological and nutrient enrichment trends in the upper Potomac (Figure 7). Prior to the 1920's, the phosphorus loading was 1,100 lbs/day or four percent of today's loading. Similarly, the nitrogen loading was 6,400 lbs/day or 10 percent of today's wastewater contribution.

The nutrient concentrations in the upper estuary under summer conditions before 1920 were estimated to be 0.04 to 0.07 mg/l of phosphorus with inorganic nitrogen ranging from 0.15 to 0.30 mg/l. With a reversion to these concentrations, not only should there be a significant reduction in the blue-green algal population, but there should also be a general reversal in the ecological community succession.

7. Specific Criteria

a. Freshwater Portion

Based upon the methodology reported above, the following nutrient criteria were developed for reversing the eutrophication process occurring in the freshwater portion of the Potomac Estuary:

Parameter	Concentration Range
Inorganic Nitrogen	0.30 - 0.5 mg/l
Total Phosphorus	0.03 - 0.1 mg/l

Since there was over 5.0 mg/l of inorganic carbon in the estuary, even under maximum bloom conditions, no criteria for carbon could be established at the present time.

The lower values in these ranges are to be applied to the freshwater portion of the middle reach and to the embayment portions of the estuary in which the environmental conditions are more favorable toward algal growth. The upper ranges of the criteria are more applicable to the upper reach of the Potomac Estuary which has a light-limited euphotic zone of usually less than two feet.

These criteria, along with a high degree of carbon removal for enhancement of dissolved oxygen should not only reverse eutrophication trends in the freshwater portion of the estuary but should also create an environment favorable for reversal of ecological succession which has occurred in the Potomac Estuary. This reversal has also occurred in the lakes surrounding Madison, Wisconsin [13] and Lake Washington [7] when wastewater discharges were removed from the lakes.

b. Meschaline Portion

Studies of the Potomac Estuary showed a relatively sharp transition from freshwater to a typical mesohaline environment corresponding to rapid in areas of salinity. At the upper end of the 22-mile reach at Maryland Point, there are primarily freshwater phytoplankton and zooplankton populations. Above Maryland Point, the salinities are less than two parts per thousand. Predominately marine forms dominate the lower end of the transition zone at the Route 301 Bridge with salinities in summer approximating 12 parts per thousand.

Based on the past five years of field studies, it appears that the growth of massive blue-green algal mats are apparently restricted to the freshwater portions. In the mesohaline environment, dinoflagellates were often encountered in "red tide" proportions.

These observations lead to two points of emphasis in estuarine water quality management:

(1) Fairly discrete biotic provinces may be identified within a given reach of the estuary, responding differently to a given stress.

(2) There is insufficient evidence to date to generalize on nutrient parameters and hypertrophic conditions in all portions of a given estuary.

Therefore, at the present time no specific nutrient criteria have been established for the mesohaline portion of the Potomac Estuary.

WASTEWATER TREATMENT REQUIREMENTS

Under controlled conditions, as reported by various investigators, reductions in the standing crop of algae can be achieved by the management of either carbon, nitrogen, or phosphorus or by a combination of these basic nutrients. The decision as to which nutrient or nutrients in a natural system should be controlled by removal from point sources may depend upon many factors including the four listed below:

1. Level of algal reduction required to minimize adverse effects on water quality,

2. Minimum nutrient requirements to maintain a given algal standing crop,

3. Controllability and mobility of a given nutrient within the system, and

4. The overall water quality management needs, such as DO enhancement, eutrophication reversal, and reduction of potentially toxic matter including heavy metals.

In establishing the overall wastewater management program for the Potomac Estuary, the need for a high degree of carbonaceous and nitrogenous UOD removal was determined along with the need for a 75-90 percent reduction in algal standing crop. Since carbon can only be controlled to a maximum of 55 percent, excluding any contribution from air-water or water-mud interfaces, control of either nitrogen or phosphorus or both is required. To provide for algal control, maximum concentration limits for both nitrogen and phosphorus were adopted.

Limits for both were incorporated for the following reasons:

(1) Since the flow of the Potomac River is very flashy, neither phosphorus nor nitrogen can be controlled throughout the estuary at all times. To reduce eutrophication in the entire estuary for years having average or above average flow conditions, phosphorus control appears to be more feasible. However, in the middle and upper estuary during low-flow years, nitrogen control appears to be more effective. This is because the nitrogen criterion for restricting algal growth is ten times that for phosphorus (0.30 versus 0.03 mg/l) while the nitrogen loading from the wastewater treatment facilities is 2.4 times that of phosphorus (60,000 versus 24,000 lbs/day). Considering only the magnitude of the limiting nutrient concentrations and the magnitude of the percentage of the wastewater contribution, this results in more than a fourfold advantage in removing nitrogen over that of phosphorus.

(2) Various investigators report that increases in nitrogen and/or phosphorus can increase heterotrophic activity which in turn stimulates algal growth, and

(3) There is compatibility between wastewater treatment requirements for dissolved oxygen enhancement and eutrophication control.

Compatibility of treatment requirements is probably one of the most important considerations of the four factors influencing the selection of wastewater treatment unit processes. For example, to maintain the dissolved oxygen standard in the upper estuary under summer conditions, a high degree of carbonaceous and nitrogenous

oxygen demand removal is required, whereas the control of algal standing crops is predicated on phosphorus and nitrogen removal. To obtain a high degree of carbonaceous oxygen demand removal, a chemical coagulation unit process is usually required beyond secondary treatment. This unit process will also remove a high percentage of phosphorus. The removal of the nitrogenous demand can be satisfied by one of two methods: (1) by converting the unoxidized nitrogen to nitrates (commonly called nitrification), or (2) by removal of nitrogen completely. If a unit process such as biological nitrification-denitrification is employed, both the DO and algal requirements for nitrogen can be met.

Thus with proper selection of wastewater treatment unit processes, it is feasible not only to enhance the DO by removing the carbonaceous and nitrogenous UOD but also to reduce nuisance algal growth by removing nutrients.

A WATER QUALITY MANAGEMENT PROGRAM

The conferees of the Potomac River-Washington Metropolitan Area Enforcement Conference agreed on May 8, 1969, to limit the amount of UOD, phosphorus, and nitrogen which could be discharged into the upper estuary from wastewater treatment facilities. The water quality management program currently being developed recognizes a need not only for high degrees of wastewater treatment for the removal of carbonaceous and nitrogenous UOD but also a need for the control of eutrophication.

Segmenting the upper estuary into three 15-mile zones (Figure 21), maximum lbs/day loadings were established for Zone I equivalent to 96 percent removal of BOD_5, 96 percent of phosphorus, and 85 percent of nitrogen. These percent removals were also adopted for discharges in Zone II until firmer loadings could be developed.

Since May 1969, more detailed loadings have been developed and presented to the conference in the December 1970 progress meeting [18]. The program calls for the construction of advanced wastewater treatment facilities by 1977 capable of removing the above designated percentages of carbon, nitrogen, and phosphorus, with possible advancement of the construction deadline to December 1974.

Present worth cost of the additional wastewater treatment required, including operation, maintenance, and amortization for the time period 1970 to 2020 has been estimated to be $1.2 billion with a total average annual cost of $54.8 million. The unit processes assumed include

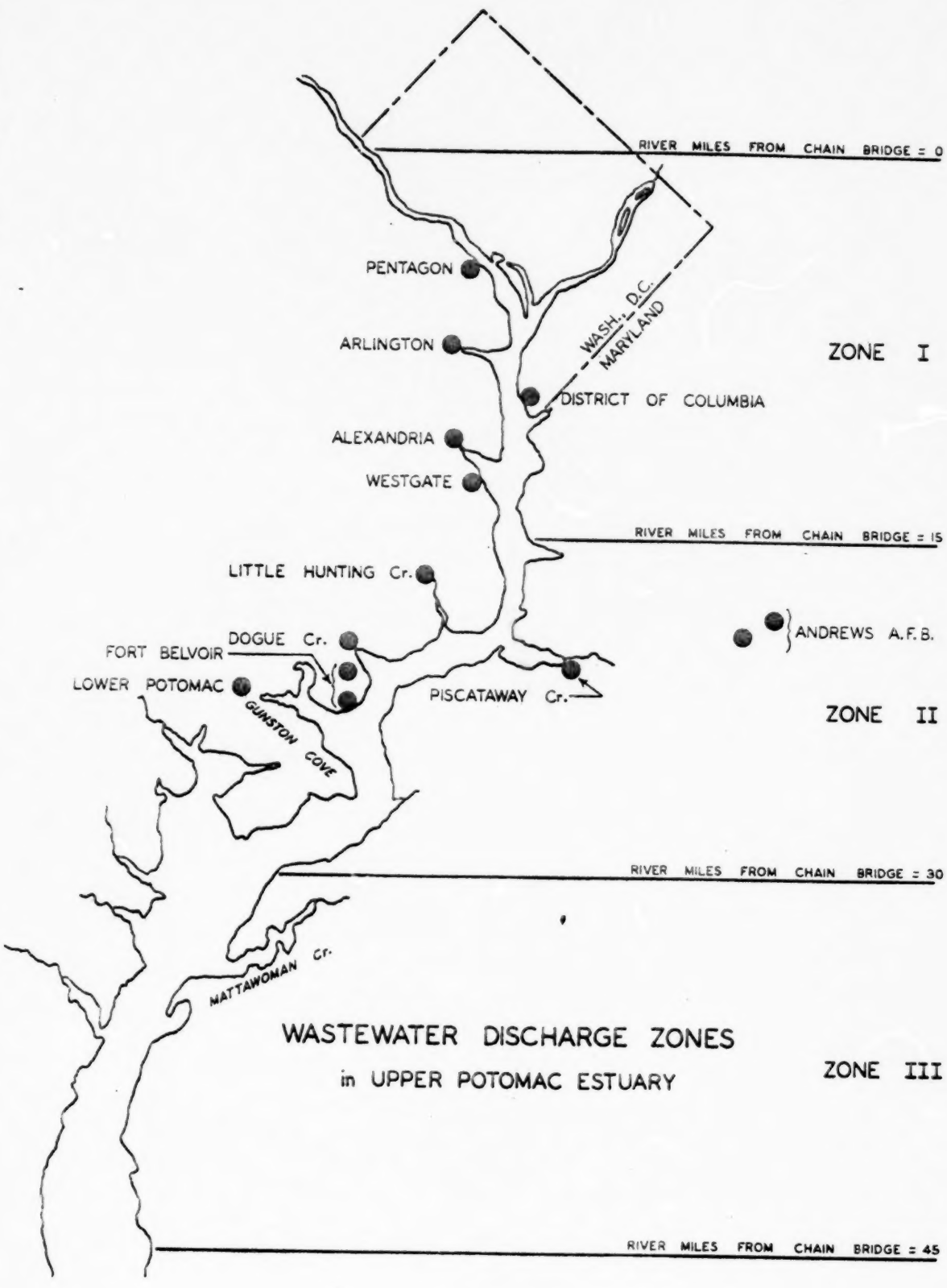

RIVER MILES FROM CHAIN BRIDGE = 0
PENTAGON
ARLINGTON
WASH., D.C.
MARYLAND
ZONE I
DISTRICT OF COLUMBIA
ALEXANDRIA
WESTGATE
RIVER MILES FROM CHAIN BRIDGE = 15
LITTLE HUNTING Cr.
ANDREWS A.F.B.
DOGUE Cr.
FORT BELVOIR
LOWER POTOMAC
GUNSTON COVE
PISCATAWAY Cr.
ZONE II
RIVER MILES FROM CHAIN BRIDGE = 30
MATTAWOMAN Cr.
WASTEWATER DISCHARGE ZONES
in UPPER POTOMAC ESTUARY
ZONE III
RIVER MILES FROM CHAIN BRIDGE = 45

FIGURE 21

activated sludge, biological nitrification-denitrification, lime clarification, filtration, effluent aeration and chlorination. On a per capita basis, the cost of the wastewater removal program is estimated to be approximately $13.50 to $18.30/person/year.

The program being developed will not only enhance the water quality of the estuary to meet minimum designated standards but will render it a feasible source of municipal water supply. Studies indicate that either indirect or direct reuse of renovated wastewater is a viable alternative in meeting the water supply needs for the Washington, D. C. Metropolitan Area [15] [17].

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